COLLISION AVOIDANCE FEATURES: INITIAL RESULTS

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ABSTRACT

Objective Analysis examined how individual collision avoidance features affected losses under a variety of insurance coverages for vehicle damage and injuries.

Methods Five automakers supplied identification numbers of vehicles that had each feature, allowing a comparison of the insurance records for those vehicles that included the optional feature with the same models without the feature. Coverage and loss data were supplied by insurers representing over 80 percent of the U.S. private passenger vehicle insurance market. Regression analysis was used to quantify the effect of each vehicle feature while controlling for the other features and covariates, including driver age and gender, garaging state, and collision deductible. Claim frequency was modeled using a Poisson distribution. Claim severity was modeled using a Gamma distribution. Estimates for overall losses were derived from the frequency and severity models.

Results Forward collision avoidance systems, particularly those that can brake autonomously, along with adaptive headlights, showed the biggest claim reductions. Other systems, such as blind spot detection and park assist, did not show consistent effects on crash patterns across different manufacturers. Lane departure warning systems were associated with increased claim rates; however, the 95% confidence intervals were large, indicating the results are uncertain. Forward collision avoidance systems with autonomous braking showed 10-14 percent reductions in the frequency of claims to repair damage that the studied vehicles caused to other vehicles; adaptive headlights showed reductions of as much as 10 percent in the same types of claims. Consistent with this finding, injury liability claims also were reduced. Both systems were associated with more modest reductions in the frequency of claims to repair studied vehicles. Forward collision avoidance systems without autonomous braking also reduced claims for damage and injuries but to a lesser extent.

Conclusion Insurance data show some collision avoidance technologies are preventing crashes and injuries. In the case of forward collision avoidance systems, the largest crash reductions involve damage to other vehicles. That is consistent with a reduction in rear-end crashes, the particular hazard these systems are meant to address. Adaptive headlights also appear to prevent collisions with other vehicles, but it is unclear why they aren't more effective at preventing single-vehicle collisions. Insurance data provide a first look at the overall effectiveness of these systems, but detailed crash information is limited. Most systems can be deactivated by the driver, and the status of a feature at the time of the crash is not known. Deactivation could partially account for the lack of demonstrated benefit for certain features. These analyses estimate real-world effectiveness of several crash avoidance technologies. While some results indicate the need for further investigation, it is clear that certain systems, such as those that help drivers avoid collisions with the vehicle in front or better illuminate the road ahead, can play a role in making roads safer.

Keywords Collision avoidance; forward collision avoidance; adaptive headlights; lane departure warning; autonomous emergency braking; blind spot; rear collision avoidance

INTRODUCTION

Collision avoidance technologies are becoming popular in U.S. motor vehicles. According to information collected by the Highway Loss Data Institute (HLDI), 211 model 2013 vehicles are available with forward collision warning (FCW), and 107 include some form of autonomous emergency braking (AEB). In addition, 146 current models have lane departure warning (LDW), 244 have blind spot information systems, and 250 have adaptive headlights. Both FCW and LDW are technologies recommended by the U.S. Government's New Car Assessment Program (NCAP). These features are optional on the 2013 model Honda Accord, one of the best-selling cars in the U.S. Not surprisingly, automakers tout the potential safety benefits of these systems as reason to buy their products.

This enthusiasm is not without reason. Several studies estimate large potential benefits. A study by the Insurance Institute for Highway Safety (IIHS) suggests that a combination of four technologies – side view assist, forward collision warning/mitigation, lane departure warning/prevention, and adaptive headlights – on all vehicles might prevent or mitigate up to 1,866,000 crashes each year, including 149,000 serious and moderate injury crashes and 10,238 fatal crashes (Jermakian, 2011). Other studies trying to predict the benefits of systems with specific characteristics also have found impressive possible benefits. For example, the National Highway Traffic Safety Administration predicts that AEB meeting certain requirements could prevent 13,000-28,000 minor injuries and 500-700 serious injuries and save 38-65 lives (NHTSA, 2012). However, few studies have measured the actual benefits of these systems.

One of the first studies to document the real-world benefits of new crash avoidance technology found that Volvo's City Safety, a low-speed AEB system, reduced crashes involving damage to other vehicles by 26 percent (see *Status Report*, July 19, 2011, HLDI, 2011). Studies by Volvo found similar benefits, and a study by the German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft, or GDV) found similar crash reductions for Ford Focus models equipped with a similar system (Isaksson-Hellman and Lindman, 2012; Hummel et al., 2011). Otherwise, there have been few analyses of the real benefits of new crash avoidance technologies.

It's not surprising that the studies that have documented the benefits of crash avoidance technologies involved insurance data. Unlike databases of police-reported collisions, insurance databases are compiled in real-time to facilitate the settling of claims for crash losses. In contrast, the Fatal Accident Reporting System (FARS), which is a census of fatal crashes in the U.S., is typically not publicly available until a year after crashes occur. Complete databases of police-reported crashes in individual states have even longer lag times. The HLDI database, which covers 80 percent of the private passenger vehicle insurance market in the U.S., is unique in that it is updated three times yearly. Furthermore, more crashes are reported to insurers than to the police, and police-reported property damage only crashes outnumber fatal crashes by more than 100 to 1. Consequently, HLDI's database offers the possibility to measure the effects of crash avoidance technologies well before data on fatal crashes or police-reported crashes are available to the public.

This study uses the insurance data in the HLDI database to examine the early insurance claims experience for Acura, Buick, Mazda, Mercedes-Benz, and Volvo models equipped with various collision avoidance features.

METHODS

Insurance data

Automobile insurance covers damages to vehicles and property, as well as injuries to people involved in crashes. Different insurance coverages pay for vehicle damage versus injuries, and different coverages may apply depending on who is at fault. The current study is based on property damage liability, collision, bodily injury liability, personal injury protection, and medical payment coverages.

Because different crash avoidance features may affect different types of insurance coverage, it is important to understand how coverages vary among the states and how this affects inclusion in the analysis. Collision coverage insures against vehicle damage to an at-fault driver's vehicle sustained in a crash with an object or other vehicle. This coverage is common to all 50 states. Property damage liability (PDL) coverage insures against damage that at-fault drivers cause to other people's vehicles and property in crashes. This coverage exists in all states except Michigan, where vehicle damage is covered on a no-fault basis (each insured vehicle pays for its own damage in a crash, regardless of who is at fault). Coverage of injuries is more complex. Bodily injury (BI) liability coverage insures against medical, hospital, and other expenses for injuries that at-fault drivers inflict on occupants of other vehicles or others on the road. Although motorists in most states may have BI coverage, this information is analyzed only in states where the at-fault driver has first obligation to pay for injuries (33 states with traditional tort insurance systems). Medical payment coverage (MedPay), also sold in the 33 states with traditional tort insurance systems, covers injuries to insured drivers and the passengers in their vehicles, but not injuries to people in other vehicles involved in the crash. Seventeen other states employ no-fault injury systems (personal injury protection coverage, or PIP) that pay up to a specified amount for injuries to occupants of involved-insured vehicles, regardless of who is at fault in a collision. The District of Columbia has a hybrid insurance system for injuries and is excluded from the injury analysis.

Insurance measures

Claim frequency is defined as the number of claims for a group of vehicles divided by the exposure for that group, expressed as claims per 100 or 1,000 insured vehicle years. Exposure is the length of time a vehicle is insured under a given coverage type and is measured in insured vehicle years. An insured vehicle year is one vehicle insured for one year, two for six months, etc. Claim severity is the total of all loss payments made for the claims for a group of vehicles divided by the number of claims paid. Claim severity is measured in dollars paid to settle a claim. It is not a measure of the change in velocity in a crash or injury severity. Overall losses for a group of vehicles is the product of claim frequency and claim severity, expressed as dollars per insured vehicle year. This is an insurance measure and represents the average annual payout for a vehicle or feature. For the injury coverages, only claim frequencies were analyzed because injury claims can take years to develop full costs. Table 1 lists the exposure, measured in insured vehicle years and claims by manufacturer for collision coverage.

Table 1.
Collision exposure and claims by manufacturer

Manufacturer	Exposure (Insured vehicle years)	Claims
Acura	218,201	15,591
Buick	171,777	11,828
Mazda	621,594	45,929
Mercedes-Benz	7,066,981	509,093
Volvo	631,664	41,012

Vehicles

Collision avoidance features are offered as optional equipment on various Acura, Buick, Mazda, Mercedes-Benz, and Volvo models. The presence or absence of these features is not discernible from the information encoded in the vehicle identification numbers (VINs), but rather, this must be determined from build information maintained by the manufacturer. Manufacturers supplied HLDI with the VINs for any vehicles equipped with at least one collision avoidance feature. Table 2 shows available features by automaker. The values given in Table 2 correspond to the exposure (insured vehicle years) for the vehicles equipped with the technology. Vehicles of the same model year and series not identified by the manufacturers were assumed not to have these features, and thus served as the control vehicles in the analysis.

Table 2.
Collision exposure (insured vehicle years) by manufacturer and feature

	Acura	Buick	Mazda	Mercedes-Benz	Volvo
FCW				72,345	6,353
FCW with autobrake	13,570			32,978	5,324
LDW		28,414		6,884	5,324
Blindspot	5,766	28,414	116,222	14,660	96,470
Adaptive headlights	168,056		20,997	652,616	66,172
Other lighting technologies				1,545,163	
Rear cameras			120,436	502,389	
Other parking features		105,588		872,200	

Statistical methods

Regression analysis was used to quantify the effect of each vehicle feature while controlling for the other features and several covariates. The covariates included calendar year, model year, garaging state, vehicle density (number of registered vehicles per square mile), rated driver age group, rated driver gender, rated driver marital status, deductible range (collision coverage only), and risk.

For insurance purposes the rated driver is the one who typically is considered to represent the greatest loss potential for the insured vehicle. In a household with multiple vehicles and/or drivers, assignment of drivers to vehicles varies by insurance company and by state, but usually it reflects the driver most likely to operate the vehicle. Information on the actual driver at the time of a collision is not available in the HLDI database.

For insurance purposes the garaging state and zip code are the location of the rated driver's primary residence. The HLDI database does not include information about the location of crashes. The vehicle density assignment is based on the garaging ZIP code.

For each safety feature supplied by the manufacturer a binary variable was included. Based on the model year and series a single variable called SERIESMY was created for inclusion in the regression model. Statistically, including such a variable in the regression model is equivalent to including the interaction of series and model year. Effectively, this variable restricted the estimation of the effect of each feature within vehicle series and model year, preventing the confounding of the collision avoidance feature effects with other vehicle design changes that could occur from model year to model year.

Claim frequency was modeled using a Poisson distribution, whereas claim severity (average loss payment per claim) was modeled using a Gamma distribution. Both models used a logarithmic link function. Estimates for overall losses were derived from the claim frequency and claim severity models. Estimates for frequency, severity, and overall losses are presented for collision and property damage liability. For PIP, BI and MedPay only frequency estimates are presented.

A separate regression was performed for each feature, coverage type, and insurance loss measure for a total of 15 regressions per manufacturer. More than 350 regression models were constructed. For space reasons, only the estimates for the individual crash avoidance features are shown on the following pages. Details of the regression models are not included in this report. To further simplify the presentation, the exponent of the parameter estimate was calculated, 1 was subtracted from the exponent, and that value was multiplied by 100. The resulting number corresponds to the effect of the feature on the loss measure.

RESULTS

Forward collision avoidance

Forward collision warning systems alert the driver if the vehicle is gaining on the traffic ahead so quickly that it is likely to crash. Some of these systems also are equipped with autonomous braking, meaning the vehicle will brake on its own if the driver doesn't respond in time.

Five different systems offered by Acura, Mercedes-Benz, and Volvo were evaluated. Mercedes-Benz and Volvo both had systems with and without auto brake functionality. The results indicate that forward collision avoidance systems are reducing insurance claim frequencies. The Acura system and both of the Mercedes systems showed reductions in claim frequency for all coverage types. The Volvo systems showed claim frequency reductions under collision, PDL, and BI liability. The results also indicate that the systems with auto brake functionality provide more benefit than those without. The Volvo and Mercedes-Benz systems with auto brake had larger reductions in PDL and BI claim frequencies than those without.

The results indicate that the systems are associated with increases in claim severity. With the exception of the Volvo system with auto brake, the forward collision avoidance systems were associated with increases in collision and PDL claim severity. Overall losses for collision and PDL were generally down. The systems with increases in overall losses were all due to increases in claim severity as opposed to increases in claim frequency. Table 3 summarizes these results.

Table 3.
Change in insurance losses for forward collision avoidance

Claim frequency					
Coverage type	Acura with auto brake	Mercedes-Benz with auto brake	Mercedes-Benz without auto brake	Volvo with auto brake	Volvo without auto brake
Collision	-3.1%	-7.1%*	-3.1%	-2.9%	-6.6%
PDL	-14.2%*	-14.3%*	-7.1%*	-10.0%	-7.1%
BI	-15.0%	-16.0%	-4.0%	-31.9%	-9.2%
MedPay	-3.0%	-21.1%	-23.1%*	13.3%	-27.5%
PIP	-16.5%	-15.1%	-1.7%	21.3%	14.0%
Claim severity					
Collision	0.6%	2.6%	14.8%*	-4.2%	10.4%
PDL	2.5%	4.3%	2.0%	-3.1%	9.9%
Overall losses					
Collision	-2.5%	-4.6%	11.2%*	-7.0%	3.1%
PDL	-12.1%	-10.5%	-5.2%	-12.8%	2.2%

Significant results are indicated by *

Adaptive headlights

Adaptive headlights respond to steering input to help a driver see around a curve in the dark. The headlights' horizontal aim is adjusted based on the speed of the vehicle, direction of the steering wheel, and other factors so that the lights are directed where the vehicle is heading. Systems from Acura, Mazda, Mercedes-Benz, and Volvo were evaluated.

The results indicate that adaptive headlights are associated with reductions in insurance claim frequencies. Of the 20 measures of claim frequency in the study, 19 showed reductions and many were statistically significant. However, these systems are all associated with increases in collision claim severity ranging from 0.3 to 3.5 percent.

Overall losses for collision results were mixed, with half showing increases and half showing decreases, while all of the PDL estimates show decreases. The largest decrease was for Mazda at a statistically significant 23 percent. Table 4 summarizes these results.

Table 4.
Change in insurance losses for adaptive headlights

Claim frequency				
Coverage type	Acura	Mazda	Mercedes-Benz	Volvo
Collision	-2.0%	-6.4%*	-0.8%	-0.7%
PDL	-6.3%	-10.1%*	-4.7%*	-9.0%*
BI	8.7%	-12.5%	-9.9%*	-16.8%*
MedPay	-28.2%	-28.9%*	-14.0%*	-6.3%
PIP	-7.9%	-28.8%*	-1.9%	-6.6%
Claim severity				
Collision	0.3%	3.3%	3.2%*	3.5%
PDL	-0.3%	-14.3%*	1.4%	-1.1%
Overall losses				
Collision	-1.7%	-3.3%	2.3%	2.8%
PDL	-6.6%	-23.0%*	-3.4%	-10.0%*

Significant results are indicated by *

Lane departure warning

Lane departure warning identifies lane markings and indicates if the vehicle path deviates from the lane and the turn signal is not on. Evaluated systems included those from Buick, Mercedes- Benz, and Volvo.

Buick and Mercedes systems were associated with higher claim frequencies under collision and PDL coverages. The Volvo system showed a reduction in claim rates under these coverages, as well as BI liability, however Volvo's system is bundled with forward collision warning with autonomous braking. Claim frequencies for injuries under PIP and MedPay showed increases for all three manufacturers, although the results were not statistically significant. Table 5 summarizes these results.

Table 5.
Change in insurance losses for lane departure warning

Claim frequency			
Coverage type	Buick	Mercedes- Benz	Volvo
Collision	4.2%	5.6%	-2.9%
PDL	7.2%	10.9%	-10.0%
BI	-1.5%	-2.8%	-31.9%
MedPay	12.5%	106.5%	13.3%
PIP	11.6%	10.6%	21.3%
Claim severity			
Collision	-1.1%	18.2%*	-4.2%
PDL	2.0%	5.2%	-3.1%
Overall losses			
Collision	3.0%	24.9%*	-7.0%
PDL	9.3%	16.6%	-12.8%

Significant results are indicated by *

Blind spot information

Blind spot information alerts drivers to vehicles that are adjacent to them. The purpose of this technology is to reduce or prevent crashes that occur during lane-change maneuvers. Acura, Buick, Mazda, Mercedes-Benz, and Volvo systems were evaluated.

Only the Acura system showed a clear reduction in collision claim frequency. Three of the five systems were associated with reductions in PDL claim frequency. The Mazda system was associated with a statistically significant reduction of 7.5 percent. Three of the five systems were associated with reductions under MedPay coverage. Under BI liability all but the Acura system showed reductions, while under PIP coverage Acura, Buick, and Volvo showed an increase.

Under collision claim severity, Buick, Mercedes-Benz, and Volvo systems showed decreases, while the Acura system showed an increase, and the Mazda system showed a near zero effect. Under PDL coverage three of the five estimates indicate a decrease although none are significant.

For collision coverage the Acura and Buick systems were associated with an increase in overall losses, while the other three systems were associated with decreases. All systems with the exception of Buick showed a decrease in overall losses for PDL coverage. Table 6 summarizes these results.

Table 6.
Change in insurance losses for blind spot information

Claim frequency					
Coverage type	Acura	Buick	Mazda	Mercedes-Benz	Volvo
Collision	-5.4%	4.2%	0.0%	-0.1%	1.3%
PDL	-16.2%	7.2%	-7.5%*	0.4%	-2.4%
BI	24.1%	-1.5%	-20.9%*	-3.6%	-6.2%
MedPay	-5.0%	12.5%	-23.9%*	-26.5%	-11.4%
PIP	43.1%	11.6%	-14.5%*	-7.2%	3.9%
Claim severity					
Collision	6.5%	-1.1%	-0.5%	-7.8%	-3.7%*
PDL	-6.7%	2.0%	2.3%	-5.5%	-1.0%
Overall losses					
Collision	0.7%	3.0%	-0.4%	-8.0%	-2.5%
PDL	-21.8%	9.3%	-5.3%	-5.1%	-3.4%

Significant results are indicated by *

Rear park assist

Rear park assist is designed to detect objects behind the rear bumper and warn the driver of its presence. These systems are intended to aid in low-speed maneuvers. Buick and Mercedes-Benz systems were evaluated.

The Buick system was associated with statistically significant reductions in collision and PDL frequencies. The PDL reduction for the Buick system was more than 16 percent. The Mercedes-Benz system was associated with a small increase in collision claim frequency and a small reduction in PDL frequency, although neither of these estimates reached statistical significance. The Mercedes-Benz systems were associated with statistically significant reductions in claim frequency of about 7 percent under MedPay and PIP. Both systems showed increases in claim severity for collision and PDL.

Overall losses for collision and PDL for the Buick system showed reductions, while the Mercedes-Benz system was associated with increases. Table 7 summarizes these results.

Table 7.
Change in insurance losses for rear park assist

Claim frequency		
Coverage type	Buick	Mercedes- Benz
Collision	-5.0%*	0.8%
PDL	-16.6%*	-1.8%
BI	-0.8%	0.5%
MedPay	-12.3%	-6.7%*
PIP	4.7%	-7.3%*
Claim severity		
Collision	1.6%	5.0%*
PDL	1.8%	4.2%*
Overall losses		
Collision	-3.4%	5.8%*
PDL	-15.1%*	2.3%

Significant results are indicated by *

Rear cameras

Rear cameras are also designed to aid in low- speed maneuvers. Systems were evaluated from Mazda and Mercedes-Benz.

Claim frequencies for both systems increased under collision coverage. The increase for the Mazda system was a statistically significant 3.1 percent. However, both systems showed reductions under PDL coverage. Claim frequency results were mixed for the injury-related coverages.

Collision claim severity increased a statistically significant 3.2 percent for the Mazda system. There was little change for Mercedes-Benz. Both systems were associated with increases in claim severity under PDL coverage.

Both systems were associated with increases in overall losses for collision coverage. The Mazda system showed a decrease under PDL while Mercedes-Benz showed an increase. Table 8 summarizes these results.

Table 8.
Change in insurance losses for rear cameras

Claim frequency		
Coverage type	Mazda	Mercedes- Benz
Collision	3.1%*	0.5%
PDL	-2.3%	-0.5%
BI	-3.1%	10.8%
MedPay	0.6%	1.3%
PIP	-2.1%	-4.0%
Claim severity		
Collision	3.2%*	-0.1%
PDL	1.3%	3.2%
Overall losses		
Collision	6.4%*	0.4%
PDL	-1.1%	2.7%

Significant results are indicated by *

Mercedes-Benz had the widest range of collision avoidance features of any manufacturer. Some of the other features showing significant reductions in PDL claim frequency include high intensity discharge lights (-5.5 percent) and night view assist (-8.1 percent). Adaptive high beams also showed a reduction in PDL claims, but the result was not significant (-5.9 percent). Active cornering lights (1.7 percent) and park guidance (5.0 percent) resulted in nonsignificant increases.

DISCUSSION

The results for forward collision warning with and without braking are encouraging. Claim frequencies show reductions across all coverage types and manufacturers. The pattern of findings for vehicle damage coverages is consistent with the expected benefits; that is, the reduction in claims is greater for PDL coverage than for collision coverage. Forward collision warning systems are intended to reduce the occurrence and/or severity of front-to-rear collisions, and those types of crashes are more common among PDL claims than among collision claims, which include many single-vehicle crashes.

Forward collision systems that include autonomous braking prevent up to twice as many claims as those without autonomous braking, despite the fact that the autonomous braking systems studied here are described by their manufacturers as being primarily designed to mitigate crash severity. This is possible because not all crashes result in insurance claims since the involved vehicles may not suffer damage if the speed is sufficiently reduced. Thus, systems with autonomous braking prevent more claims than those without because the autonomous intervention backs-up drivers who fail to respond to the warnings or respond too slowly. There are also other differences between systems with and without autonomous braking that may help explain the larger benefit of those with braking. For example, Volvo's system without auto brake is functional only at speeds over 20 mph, while the version with auto brake starts working at 3 mph.

All four adaptive (steerable) headlight systems show benefits for most coverages, and many of these estimated reductions are statistically significant. The analysis indicates a benefit in claims reduction, but the pattern is not consistent with expectations. For example, the prevalence of single-vehicle crashes at night suggests that adaptive lighting would have a greater effect on collision coverage than PDL. However, to the extent that this feature is effective, it appears to reduce PDL claims more than collision claims. Making the pattern even more perplexing is the fact that just 7 percent of police-reported crashes occur between 9 p.m. and 6 a.m. and involve more than one vehicle, and even fewer occur on curves where adaptive lights would seem to have the greatest benefit over those that are not steerable. Given the reductions in PDL claim frequency (5 to 10 percent), this would mean that nearly all nighttime PDL claims were prevented. This raises questions about the exact source of the estimated benefits: Does steerable lighting work because the lamps are steerable or is there something else about cars with active lighting, such as brightness or range, which has not been adequately accounted for in the current analysis?

This analysis show higher claims for Buick and Mercedes models equipped with lane departure warning. Only Volvo's system showed a nonsignificant benefit, which may not be due to the LDW system. Volvo's LDW is always bundled with FCW among the studied population. Noting the benefits of FCW among other manufacturers' products, it seems plausible that FCW and not LDW explains claim reductions.

The lack of a benefit for LDW is disappointing because earlier estimates of the potential benefits suggested that LDW could possibly prevent more than 7,000 fatalities annually if it could significantly prevent single-vehicle run-off-road crashes, many of which end in death (Jermakian, 2011). It's possible that LDW systems are preventing such crashes without being detected in these analyses because fatal crashes make up a very small proportion of insurance claims. Nevertheless, the increase in damage and first-party injury claims raises questions about whether the predicted benefits of LDW will be realized.

The results for blind spot information, park assist and rear cameras did not show clear effects. The results for Mazda's blind spot information system were encouraging, with significant reductions in claim frequency for 4 of 5 insurance coverage types. However, the lack of an effect on collision claims is puzzling. The lack of confirmatory findings for other manufacturer's blind spot systems raises questions about the robustness of this finding. Similarly, the park assist system in Buicks significantly reduced the frequency of claims under both collision and PDL, but the lack of similar effects for the Mercedes-Benz system or rear camera systems from either of the two automakers studied undermines confidence in this result. It's possible that more data will bring the results from the different manufacturers more in line with each other.

LIMITATIONS

There are limitations to the data used in this analysis. At the time of a crash, the status of a feature is not known. The features in this study can be deactivated by the driver, and there is no way to know how many of the drivers in these vehicles turned off a system prior to the crash. If a significant number of drivers do turn these features off, any reported reductions may actually be underestimates of the true effectiveness of these systems. However, surveys of owners of vehicles equipped with crash avoidance features show that significant majorities claim to leave the systems switched on (60-90 percent) even when they report that the systems annoy them with unwanted warnings (Braitman et al., 2010, Eichelberger et al., 2012).

Data supplied to HLDI do not include detailed crash information. Information on point of impact or information on vehicle operation at the time of the event is not available. The technologies in this report target certain crash types. For example, the blind spot information system is designed to prevent sideswipetype collisions. However, all collisions, regardless of the ability of a feature to mitigate or prevent the crash, are included in the analysis. All of these features are optional and are associated with increased costs. The type of person who selects these options may be different from the person who declines them. While the analysis controls for several driver characteristics, there may be other uncontrolled attributes associated with people who select these features.

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Advanced Brake Assist – Real World effectiveness of current implementations and next generation enlargements by Mercedes-Benz

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ABSTRACT

The conventional Brake Assist System (BAS) was developed by Mercedes-Benz and became standard equipment of all Mercedes-Benz passenger cars in 1997. In its further development it was supplemented by radar sensors and adaptive brake assist functions to address rear-end collisions. Advanced Brake Assistance Systems were introduced by Mercedes-Benz in the S-Class model 221 in the year 2005 (adaptive brake assist) and completed in 2006 (autonomous partial braking), 2009 (autonomous full braking) and 2011 (expansion of the limits of the functions).

After several years of proving itself in real world accidents situations it is time to compare the prognosis of its real-world effectiveness in avoiding or mitigating the severity of rear-end collisions with the real-world results as well as discussing the expected effectiveness of the enlargements of the advanced brake assist systems to new accident situations. The paper compares the former prognosis of real-world effectiveness of the systems in avoiding rear-end collisions or mitigating their severity with results of the latest analysis based on actual crash data, FOT, insurance data and others. It will be proved that the prognosis was confirmed or exceeded in some cases. A method for a lifetime analysis will be proposed. Advanced technologies in environmental sensing, situational perception and new actuators that allow individual situation-based interventions in braking, in steering or in controlling the chassis characteristics offer new options for the enhancement of automotive safety.

INTRODUCTION

During the first decade of this century road accidents received increasing public interest. The EU set a 50% reduction in the number of fatalities among Europe by 2010 as its common goal and renewed it for 2020. The United Nations announced a "Decade of Action" 2011 to 2020 for Road Safety to reduce the number of 1.3 million people killed in road crashes every year. 90% of them happen in developing countries. Road fatalities are just the tip of an iceberg. They bring a variety of other accidents in their train. However, a multiple of other road users get physically injured. The analysis of accidents showed that rear-end collisions had a big share in all accidents with injuries worldwide. Rear-end collisions are globally considered very significant. Their share in any accident involving injuries or fatalities makes about 23% in Germany, about 28% in the U.S., about 32% in Japan and about 33% in China. (see Fig. 1)

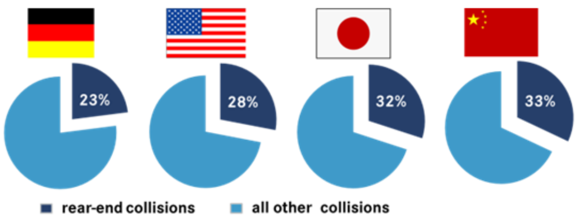

Fig. 1: Share of rear-end collisions in all accidents with casualties or fatalities (Source: 2010; DESTATIS, NHTSA, IATSS, China Min. of Public Safety)

Mercedes-Benz launches very effective primary and secondary safety measures to reduce particularly this type of accident. The systems are called PRE-SAFE® and PRE-SAFE® Brake, Forward Collision Warning, BAS PLUS, Adaptive Brake and Collision Prevention Assist just to mention only a few. In general, these systems are commonly referred to Forward Collision Avoidance Systems (FCA). Within Mercedes-Benz passenger cars FCA interact (if ordered) with PRE-SAFE® – a system offering integrated safety by anticipating an impending accident based on data shared with primary safety measures and activating protective measures in advance e.g. takes the slack out of the seat belts using reversible tensioners and, if a side impact or roll-over is considered likely, closes the power windows and sunroof [17, 18]. Accident research shows that drivers do not always react as quickly as is necessary in critical moments – for example because they are distracted and therefore do not realize the immediate threat of a rear-end crash. Main causal factors are:

- late or no reaction of the driver due to inattentiveness / distraction
- drivers non-awareness of the (increasing) criticality of the pre-crash situation
- misperception of distance and/or deceleration of the lead vehicle resulting in insufficient brake application
- demands resulting from the dynamics within the pre-crash situation exceeds the performance limits of the driver.

In almost 70 percent of these accidents the driver does apply the brake, but too late or too weak; about 30% currently do not brake. Due to this observations a general FCA system consist of at least one module out of FCW (forward collision warning), EBA (emergency brake assist) and AEB (autonomous emergency braking). AEB systems can be subdivided in CMB (autonomous collision mitigation braking) and CIB (autonomous collision imminent braking). Within Mercedes-Benz passenger cars this components have special Mercedes-Benz shaping. (for more details [1,2,4])

FCW: Forward Collision Warning System. Audible and visual warnings are issued when a collision danger is present. Warning is timed to give the driver the chance to avoid collision by braking and/or steering.

BAS PLUS (BAS+): Adaptive brake assistance (EBA) that enhances driver's braking input if necessary based on radar information to avoid a collision with a moving, stopping or stationary lead vehicle.

Adaptive Brake Assist (ABA): Adaptive brake assistance (EBA) that detects an imminent danger of collision with moving/stopping lead vehicle by using radar sensors. If the driver applies the brake in time, the system automatically provides the deceleration required to avoid the collision.

PRE-SAFE® Brake (PSB): Autonomous Emergency Braking (AEB) performed when collision danger is imminent. Stage 1 Partial Braking (CMB), Stage 2 Full deceleration (CIB; when the collision cannot be avoided). Collision can be avoided by stage 1 in combination with BAS PLUS, stage 2 reduces crash severity.

Adaptive Brake (AB): is the name of the brake system that includes support functions to enhance safety and comfort, among others "Brake drying" and "Brake priming". This hydraulic dual-circuit braking system is electronically controlled. In wet conditions the "Brake drying" function applies brief braking impulses to wipe the film of water from the brake disc. Priming means that the system is able to increase the pressure in the brake lines into light contact with the brake discs by itself. Priming supports Brake Assist, Brake Assist PLUS and Adaptive Brake Assist to brake with full force immediately when required.

Currently these safety measures are offered in two bundles as a *basic safety feature* (CPA) or as a *safety net* (DAP) of the Mercedes-Benz adaptive cruise control called DISTRONIC PLUS.

Driving Assistance Package (DAP): is the sales name of an optional bundle of FCA components in which FCW, BAS PLUS and PRE-SAFE Brake® as well as AB are included as a part of DISTONIC PLUS. It is available since 2005. All DPA functionalities cannot be switched off directly by the driver.

Collision Prevention Assist (CPA): is the **s**ales name of a bundle of FCA components in which FCW and ABA as well as AB are combined. It cannot be switched off by the driver. The system is standard on the new B-Class since 2011.

The technical characteristics are contained in Tab.1.

	CPA	DAP
Equipment type	standard	optional
Radar Sensors	1	3
Sensor Range	approx. 80 m	approx. 200 m
Adaptive Cruise Control	-	0 - 200 km/h
Headway warning**	yes	yes
Forward Collision Warning		
Moving/stopping vehicles	30 - 250 km/h	7* - 250 km/h
Stationary vehicles	30 – 72 km/h	7* - 72 km/h
Meets NHTSA requirements	yes	yes
ABA / BAS Plus		
Moving/stopping vehicles	30 – 250 km/h	7* – 250 km/h
Stationary vehicles	-	7* – 72 km/h
Autonomous Emergency Braking	-	7* – 200 km/h
Activation of (optional) reversible PRE-SAFE® functions	yes	yes

All speeds indicate own vehicle speeds.
* The operation speed range for FCW, BAS PLUS and PRE-SAFE Brake were expanded in 2010 from a lower threshold of 30km/h to 7 km/h.

** following distance below 0.8 s for 3 s or longer

NHTSA: Forward Crash Warning System Confirmation Test [12]

Tab. 1: Characteristics of CPA and DAP

In the last 10 years, many systems have appeared on the market. They all address the rear end collision. There are always papers that describe aspects of analysing the effectiveness of these systems. Currently there is no single way to do this impact analysis over the whole life cycle of a system from the concept phase through the development within the use in real world traffic. A holistic suggestion is outlined in Fig.2 [13]. Especially the feedback loop in which the effectiveness in real world is compared with the accident mechanism and a prediction is necessary.

Fig. 2: Continuous evaluation process of real world effectiveness of primary safety measures

Detailed understanding of the *accident mechanism* including the behavior of the driver that runs to the deficit and the injury causation is needed to define standards, requirements and test criterions for the system.

Dynamical tests of the system proofed the technical performance of the system in its use-cases.

Simulator studies are relevant to quantify acceptance and effectiveness of the Driver Vehicle Interaction. However, the results show the effectiveness with which the FCA or its components can address the main causal factors that lead to the accident or can be influenced too an optimal *driver-vehicle* reaction.

Field tests as a part of the development process give a realistic assessment of the change of faulty behavior by FCA components and release rates for each component of FCA and their efficiency of their cooperation in the wide range of the use-cases in the real world.

Efficiency prediction brings together different parameters like the technical performance of the system in relevant test conditions, the performance of the driver vehicle interface and the accident mechanism. Another a posteriori method is a case by case study on representative detailed data that makes use of the estimated performance indicators. However, such studies are found to be complicated and very time consuming, in particular for FCA systems.

Real world evaluation of the system can be done on different ways. An OEM has the opportunity to analyze the *calls of special spare parts* to proof the effectiveness of a FCA system (avoided collision should be reflected in reduced calls). This could be done very early after the market lunch of the system. Another method is the analysis of *insurance claim data*. After 3-4 years depending on the amount of vehicles equipped with the system these figures could be available. However, after the system is introduced it takes several additional years for it to penetrate the market. Only then it is possible to gain information on its efficiency based on real world accident statistics. Many of these systems take more than a decade of years to achieve a sufficient penetration rate.

The proposed process (Fig. 2) is illustrated exemplary for the Mercedes-Benz components of a Forward Collision Avoidance system below.

ACCIDENT MECHANISM & BASIC SAFETY POTENTIAL

The main driver deficiencies leading to rear-end collisions were outlined before. These deficiencies are addressed by CPA´s functions FCW and ABA respectively by DAP´s components FCW and BAS+ (and, to a lesser extent, Headway Warning). Breakdowns of the principal accident mechanisms of rear-end collisions based on GIDAS data shows where these functions have a potential safety impact:

- Collision partners: In at least 80% of all rear-end collisions with injury outcome a passenger car strikes another vehicle (commercial vehicles and coaches struck: approx. 8%, two-wheelers struck: approx. 6%)
- Serious injuries: In at least 90% cases, serious injuries occur in the striking passenger car at collision speeds between 30km/h and 130km/h (own vehicle speed at time of collision). In approx. 2.5% of all cases the striking car has a velocity above 130km/h. For the entire speed range, the risk of serious injury is approx. 1:1 for striking to struck passenger car occupants. The factor for slight injuries is 1:4.
- The main accident types of rear-end collision in longitudinal traffic are “vehicle and follower“, “congestion and follower”, “vehicle waiting mandatory and follower”, “vehicle turning left / right and behind”, “vehicle and lane changer” …[14]
- The amount of multi-collisions in longitudinal traffic is about 30%. The amount of multi-collisions in the case of accidents caused by congestion is above 40% [16].

→ Addressed by CPA (both FCW and ABA & BAS+). It becomes clear that CPA’s speed range clearly targets a potential in which the majority of serious injuries occur in the subject vehicle.

- In approximately 24% the road surface is wet and another 9% ice (i.e. water/salt film on brake).

→ Addressed by AB “dry braking”

- Driver behaviour in the striking passenger car:
  - In 31% the driver does not brake (NB: unknowns included here)

    → Primarily addressed by FCW (producing a braking reaction) and secondarily by ABA / BAS+ (once FCW has led to a braking reaction) if FCW does not generate any reaction addressed by PSB
  - In 69% the driver braked inadequately (too late or not hard enough).

→ "Too late" is addressed by FCW, "not hard enough" is addressed by ABA & BAS+.

Activation rate of the "classic" Brake Assist (BAS) in the striking car:
Tests with "*normal*" driver in a driving simulator in critical situations that could lead to rear-end collisions showed that the drivers activated the brake, but:

- The BAS activation rate is less than 50% [16] and
- The BAS activation rate correlates to the criticality. [16]

→ addressed by ABA & BAS+, since its activation threshold (in terms of brake pedal input) is considerably lower than that of the "classic" BAS, given that the additional environment information is available for the situation assessment.

- Analysis of accident data (GIDAS) showed that
  - At least 30% striking passenger cars showed a deceleration above 6m/s² (mean deceleration 7.7m/s²), that could be used as an indicator for activating the classic Brake Assist (BAS)
  - 70% of the striking passenger cars brake with less than 6m/s²; mean deceleration is 5.0 m/s².
  - In 52% of accidents in which the driver of the striking car actually brakes, the collision could have been avoided if the driver had picked a higher but physically feasible braking deceleration. [15]

  → addressed by ABA & BAS+

  Further observations:

  - Advancing the braking reaction by 0.1s would avoid approx. 11% of the first collisions. Another approx. 11% could be avoided for every additional 0.1s braking advancement (almost linear development in the interval [0s to 0.5s]) [3].

  → addressed by FCW & AB

  - In at least 70% of accidents in which the driver of the striking car actually brakes the collision could have been avoided if the driver had picked higher but physical feasible braking deceleration and the reaction had been advanced for 0.3s. [14]

  → addressed by FCW & ABA / BAS+ & AB

- Main accident causes reported by the police for the driver of the striking passenger car:
  - approx. 27% to low headway distance → addressed by CPA's Headway Warning
  - approx. 27% inappropriate speed → addressed by FCW as a secondary effect

The most remarkable point is that the components FCW, BAS+ and ABA, PSB in the sum address all topic and causal factors of rear-end collisions. AB gives an additional boost in braking performance. The need of a component that releases an autonomous braking in a bungle is related to the share in which an FCW is able to shift a non-braking reaction to a driver initiated braking. We will return to this problem later.

INJURY MECHANISM

Typical injury mechanisms as addressed by forward collision avoidance systems in the equipped system vehicle (own ship) are reflected well by the dummy parameters monitored in known international frontal certification and rating tests, predominantly with partial, also with full overlap.

Injury criteria include:

- head injuries caused by resultant peak accelerations, accelerations over time (as reflected in the Head Injury Criterion) and concentrated loading through body interior contacts or contact with intruding lead vehicle parts
- Neck disorders due to overloading shear, tension/compression forces or multiaxial extension moments
- Chest injuries caused by high chest acceleration, rib deflections, deflection speed related viscous criteria and concentrated loadings due to intruding objects or hard contacts with body interior parts
- Pelvis and lower extremities injuries, monitored by compression forces and bending moments

The injury mechanisms addressed in the lead vehicle correspond to those assessed in whiplash testing conducted by insurance and rating institutions that rate neck disorders according to occurring shear, tension / compression forces or multiaxial extension moments.

DAP and CPA both target at preventing or at least mitigating these injuries by helping to avoid collisions altogether or at least mitigating their severity by reducing collision speed.

EFFICIENCY PREDICTION - Safety Potential as derived from Real World Data (Prospective Analysis)

Different studies on the basis of GIDAS data show the safety potential of the driver assistance features FCW, BAS PLUS and PRE-SAFE® Brake within DISTRONIC / DISTRONIC PLUS [14], [15]. The first step was to identify a representative set of 839 rear-end collisions with injury in GIDAS data (12-2006). They were used as a base for case-by-case studies with detailed models of the vehicle and the analysed safety measure.

In a collision avoidance efficiency study for rear-end accidents, DISTRONIC and BAS were analysed and compared to DISTRONIC PLUS and BAS PLUS. All systems and the vehicle's dynamic characteristics (current S-Class type BR221) were modelled in detail. The following requirements were made: a fitment rate of 100% was assumed, DISTRONIC as well as DISTRONIC PLUS were activated in extra urban situations on freeways and highways only, driver behaviour remained unchanged, a reaction of the driver to warnings was not modelled. With these conservative assumptions the results of Fig. 3 were obtained.

The predicted efficiency of BAS based on GIDAS data is very similar to the value that was obtained from a retrospective analysis of German national accident data provided by the Federal Statistical Office (DeStatis). For DISTRONIC PLUS / BAS PLUS, a system that is not distributed widely enough in the market to allow retrospective analysis of accident data, a 20% avoidance and a 25% mitigation rate of rear-end accidents with injury are derived. The values for highways and the autobahn are even higher.

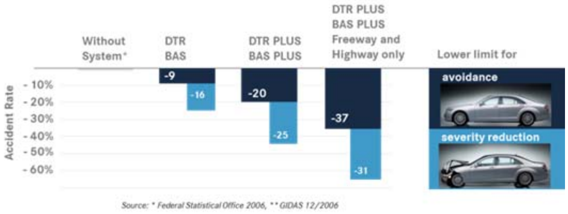

Fig. 3: Rear-end Accident Avoidance Potential of DISTRONIC with FCW and Brake Assist Based on Real World Data

CPA is similar to the analysed combination of FCW and BAS+, with the exception that ABA – the adaptive brake assist within CPA is not able to detect stationary vehicles never been detected moving before. BAS+ has this ability (Tab.1)

To compensate this difference between ABA and BAS+, a corrective factor is determined. In 2011 GDV published a study based on insurance data [8]. In this study, the safety potentials of various driver assistance systems were derived. Among others they compared the impact for a FCA system of having the characteristic to detect moving/stopping objects with the characteristic to detect moving/stopping and stationary objects. The Forward Collision Avoidance system consists of FCW, EBA and AEB.

- The FCA system that had the characteristic of detecting moving/stopping vehicles only has an accident avoidance potential of 17.8% of all passenger vehicle accidents with injury.
- The same system including additionally the detection of stationary vehicles has an accident avoidance potential of 19.6% of all passenger vehicle accidents with injury.

While the absolute efficiency percentages are deemed to be generous, it is nevertheless possible to isolate the factor quantifying the detection of stationary vehicles. The quotient of these figures is 0.91 (17.8 / 19.6). To make a rough estimation, 0.91 is applied to the 20% accident avoidance potential and the 25% severity mitigation potential derived in before (Fig.3) we get for CPA:

- an accident avoidance safety potential of 18%
- an accident severity reduction potential of 22%

for rear-end passenger vehicle crashes with injury in the bullet car.

CPA lacks the non-negligible safety spin offs of the adaptive cruise control deceleration. However, this mere comfort oriented "long range" and modest deceleration is of lesser benefit to actual accident avoidance and reliant on DISTONIC PLUS's ACC function actually being in use (primarily on highways / freeways).

DRIVING SIMULATOR TESTS TO RATE THE EFFICIENCY

To assess the effectiveness in which the two combined functions Forward Collision Warning FCW and Brake Assist PLUS are able to improve faulty driver behaviour in the case of rear-end collisions, an experiment was conducted in the Berlin dynamic driving simulator [11]. Brake Assist PLUS is equivalent with CPA's Adaptive Brake Assist with the added capability of detecting stationary vehicles. The results can directly apply to CPA, because the analysed scenarios did not contain stationary objects.

110 ordinary drivers had to cope with three typical driving situations that often lead to rear-end collisions according to accident statistics (see Table 2). They had of approximately 40minutes. One half of the sample drove a vehicle equipped with the conventional BAS, the other half had BAS PLUS available in addition to BAS. In this study, the initial travelling speed of the ego vehicle was always beyond 30 km/h and the target vehicle was always moving. Hence, CPA's Adaptive Brake Assist would have operated in the same way as Brake Assist PLUS.

Nr	Road Type	Speed [km/h]	Initial following distance [s]	Scenario
1	Autobahn	130	1.45 – 1.55	Subject vehicle on left lane, vehicle cutting in from right lane at TTC = 2 s
2	Autobahn	130	1.45 – 1.55	Lead vehicle starts to brake at1 m/s^2 for 0.7 s and then increases deceleration to 8.5 m/s^2
3	Highway	80	1.45 – 1.55	Lead vehicle starts to brake at 1 m/s^2 for 1 s and then increases deceleration to 9.0 m/s^2

Table 2: Scenarios tested in the dynamic driving

Results show that the combination of FCW and BAS

PLUS leads to a 75% lower accident rate (combined) compared to the conventional BAS (Table 3). For those subjects who reacted too late to avoid the accident, BAS PLUS produced a mitigating effect: impact speed was reduced by 35 % on average.

Scenario	Accident Rate with		Impact Speed (if collision occurred) with	
	BAS	*BAS PLUS*	*BAS*	*BAS PLUS*
1	20%	4%	30 km/h	19 km/h
2	55%	19%	60 km/h	45 km/h
3	44%	6%	46 km/h	26 km/h

Table 3: Driver performance in dynamic simulator tests (110 subjects, mean values)

All three potential accident situations would have been addressed by CPA in the same way as they were by BAS PLUS. Hence, the results of this study directly apply to CPA. From the drivers view, the driving simulator contains a "real" car. So the FCA assessed with car environment and/or its settings can be determined. The default setting for BAS PLUS is "on", as is the case for CPA.

Fig. 4: The (old) Berlin moving base simulator of Daimler

For BAS PLUS in combination with FCW it was found that it has high acceptance, a very effective driver vehicle interface and is very effective in reducing collision or collision speed. The results are valid one-to-one for CPA.

FIELD TEST RESULTS

Field tests are usually carried out in the last phase of the development. Mercedes-Benz runs integrated field tests for new and modified systems. They were performed in real world traffic mostly by non-expert drivers and carried out in Europe, US, Japan and South Africa. Generally over 1 million km were driven. The received data base allows an in-depth analysis of the system in cooperation with different driver in the wide range of pre-crash scenarios from critical situations up to near crashes. The results were used in this section to show that Collision Prevention Assist covers most relevant functions of the Driver Assistance Package. Table 4 list the differences.

	PRE-SAFE Brake	Collision Prevention Assist
Headway warning	Yes	Yes
forward collision warning	Yes	Yes
Adaptive Brake assistance	Yes	Yes
Autonomous partial braking	Yes	No
Autonomous full braking	Yes	No

Table 4: Collision Prevention Assist – Comparison with PRE-SAFE® Brake

The main difference is that CPA cannot provide autonomous braking.

To assess the magnitude of this limitation, an in-depth analysis of Mercedes-Benz field test data was carried out. The data set was generated by a special field test carried out for the modified operation speed ranges for FCW, BAS PLUS and PRE-SAFE® Brake (expanded in 2010 from the lower threshold of 30km/h to 7km/h, Tab. 1). The data basis contains 53.100 measurement ascertained in 735,000km driven by more than 400 ordinary (84%) and professional (16%) driver. No rear-end collision occurred within the field test. For more detail see [3]

System	Activation Rate [events per 100,000 km]
Forward collision warning	720
Brake Assist plus (BAS Plus)	15
Brake Assist plus (BAS Plus) AND PRE-SAVE® Brake Stage 1	1
PRE-SAVE® Brake Stage 1 (partial autonomous braking)	2,5
PRE-SAVE® Brake Stage 2 (full autonomous braking)	0

Tab 5: Mercedes-Benz field tests: system activation rates

Tab. 5 shows the activation rates of the different components of the Driving Assistance Package. The Forward Collision Warning in combination with BAS PLUS is by far the most frequently triggered driver support in critical longitudinal driving situations:

- Collision warning resolves many situations
- BAS PLUS alone is activated four times more often than autonomous partial braking
- Even when autonomous partial braking was activated, the drivers braked if necessary (and also received BAS PLUS support, if still necessary)
- No activation of autonomous full braking
- No rear-end collision occurred in the field test

During the field test each system activation was recorded with all relevant physical signal information and with video data captured by several video cameras in the test car.

For the following analysis is restricted to those activation had been qualified as correct. A subset of 379 randomly chosen FCW activations was generated to eliminate statistical influences resulting from the selection procedure. Fig. 5 showed that the majority of warnings occur between 30km/h and 80 km/h.

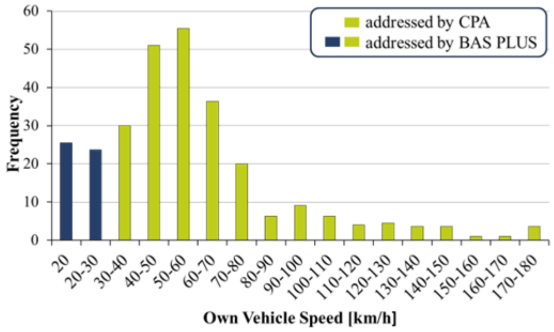

Fig. 5: Mercedes-Benz Field tests: Frequency of forward collision warnings in speed categories (n=379), warnings at speeds above 30 km/h will also be given by Collision Prevention Assist.

The driver was already braking in more than 40% of cases when Forward Collision Warning was triggered (Fig. 6), which correlates well to the results of the GIDAS study outlined in the accident mechanism. Very frequently, the situation occurs in following traffic: The car in front of the test car is already braking when it suddenly increases the deceleration and the following driver unexpectedly also needs to increase his brake force. This observation is also in good correspondence to the accident mechanism.

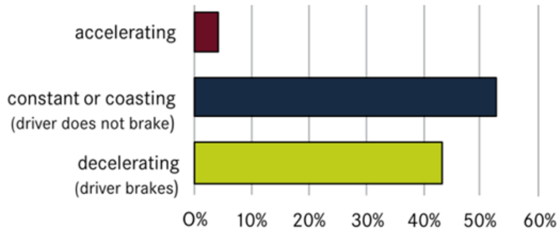

Fig. 6: Mercedes-Benz Field Analysis of field tests: vehicle state when forward collision warning was triggered

Interestingly 44% of all drivers were already braking when a FCW occurred (Fig. 7). Of the drivers who responded to FCW by applying the brake:

- 65% of acted within 0.4s after the warning
- 87% of acted within 0.8s after the warning
- 97% of acted within 1.0s after the warning

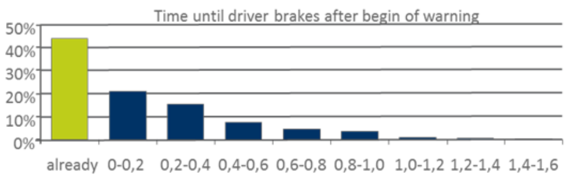

Fig. 7: Mercedes-Benz Field Analysis of field tests: Time between onset of Forward Collision Warning and driver (re)action

No FCW activation without any driver reaction was observed. Hence the audible / visual warning, a combination of warning tone and icon, proves to be very effective. However, no claim for an individual safety potential of FCW, separate from Adaptive Brake Assist, is being made in this dossier. The potential of CPA is always given as a combination of FCW and ABA.

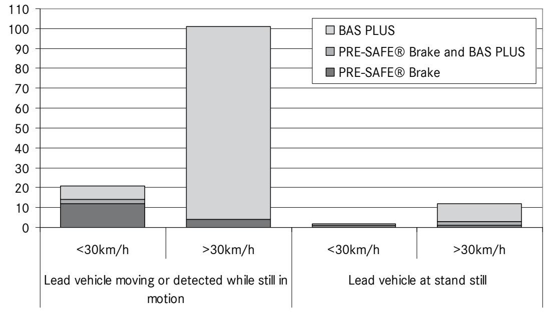

Fig. 8: Mercedes-Benz Analysis of field tests: System Activations in different speed and lead vehicle moving categories (n = 136)

Fig. 8 gives an overview to which extent each system is able to address the critical situations that have occurred during the Mercedes-Benz field tests. The full functionality of the Driver Assistance Package was able to address all of the critical situations.

- BAS PLUS was effective in 87% of all critical situations; so that no accident occurred.
- The CPA functionality had addressed 71% of all critical situations (82% out of the BAS PLUS-situations).
- PRE-SAFE® Brake stage 1 (autonomous partial braking) had addressed 13% of all critical situations.
  - PRE-SAFE® Brake stage 1 had addressed 3% of all critical situations above a threshold of 30km/h.
- Low speed brake assistance (system activations below a threshold of 30km/h) had addressed 17% of all critical situations.
  - PRE-SAFE® Brake stage 1 (autonomous partial braking) had addressed 10% of all critical situations.
  - BAS PLUS had addressed 7% of all critical situations.
- Characteristic feature “detect objects that were not moving during their first detection” for brake assistance had addressed 10% of all critical situations. (good correspondence with the GDV analysis [8])

In order to assess the relevance of these data from MB field tests with regard to real world accidents, a comparison with GIDAS data was carried out. As an indicator the distribution of speed in critical situations in the Mercedes-Benz field test and the speed distribution of accidents with personal injuries taken from GIDAS were used (Fig. 9). The speed profile of system activations in Mercedes-Benz field tests is very consistent with data on real rear-end collisions with one exception: the frequency distribution of PRE-SAFE® Brake situations is different. This finding is not really surprising: no FCW activation without any driver reaction was observed. While PRE-SAFE® Brake Stage 1 is available up to a vehicle speed of 200 km/h; it is nevertheless activated mainly at lower speeds where typically minor personal injuries (would) occur.

Not every critical situation within the Mercedes-Benz field test would have ended in an accident in real world traffic. However, it seems to be plausible that a substantial proportion of critical cases in the Mercedes-Benz field test would have led to an accident without the system's support.

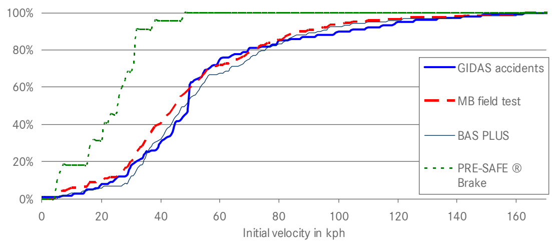

Fig. 9: Comparison between Mercedes-Benz Field test and GIDAS: Velocity at start of braking in critical situations in MB Field test and velocity of rear end crashes taken from GIDAS

The Mercedes-Benz System CPA does not provide the full functionality of the optional Driver Assistance Package consisting of PRE-SAFE® Brake BAS PLUS and FCW. However, it does provide some of the most relevant and most effective functions of the DPA portfolio. Remarkably, the CPA system could address 71% of all critical situations.

REAL WORLD EVALUATION - Mercedes - Benz Spare Part Calls Analysis

The real world evaluation is the final step in the process outlined in Fig. 2. In this paragraph the results of a spare part call analysis are represented. An OEM can analyze the calls over a fixed period and country for a model and compare the calls for vehicles that were equipped with and without a technology. Avoided collisions should lead to fewer calls of (significant) spare parts. Collisions with mitigated severity should lead to shift in spare parts needed for repairs.

To determine the effect of the driver assistance system DISTRONIC PLUS with its integrated assistance features FCW and BAS PLUS an analysis was carried out on the basis of spare part calls. The amount of spare part calls of two equal vehicle models groups equipped / not equipped with the system should differ regarding bumpers, bumpers + cross members and bumper + cross member – front end longitudinal member assembly.

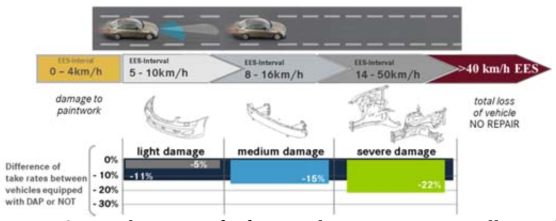

Fig. 10: Reduction of front-end spare parts calls with DISTRONIC PLUS (Model Range 221 in Germany from launch to end of 2008, about 60,000vehicle years in operation)

The evaluation was based on the data of the spare parts calls for the S-Class model 221 delivered by Mercedes-Benz in Germany between launch and end of 2008. In this period about 40,000 cars were sold and registered in Germany. About 40% of these cars were equipped with DISTRONIC PLUS including Forward Collision Warning, PRE-SAFE® Brake stage 1, BAS PLUS and parking assistance. The remaining 60% were equipped with parking assistance only. The results are shown in Fig. 10. The diagram uses the damage of spare parts as an indicator for typical energy levels (given by Energy Equivalent Speed or EES). For all observed chains the highest level is used. The Figs. demonstrate that the rate of repairs for the vehicles equipped with the DISTRONIC PLUS package was reduced in all three ranges of energy equivalent collision speeds. The rate of repairs of front-end bumpers was reduced by 5%, the repair rate of a front-end bumper in combination with a cross member dropped by 15% and repairs involving front-end bumper, cross and longitudinal member assembly dropped by 22%. These data show that DISTRONIC PLUS with the included driver assistance features including PRE-SAFE® Brake is effective in reducing the number and severity of frontal crashes significantly.

Taking the characteristics of the driver assistance safety measures (Tab. 1) into account, a calculation of the efficiency of Forward Collision Warning, BAS Plus and PRE-SAFE® Brake Stage 1 for rear end collisions with injuries or fatalities is possible. The frequency of accidents at a given level of accident severity (measured in EES) occurring in real world accidents can be determined with a cumulative sum of EES taken from a representative accident data sample, such as GIDAS. The number of accidents (respectively cars or injured occupants) occurring up to a certain accident severity can thus be determined. This analysis shows that 53% could be mitigated, as they are in a severity range of up to 45km/h EES. (Fig. 12, for more details see [15])

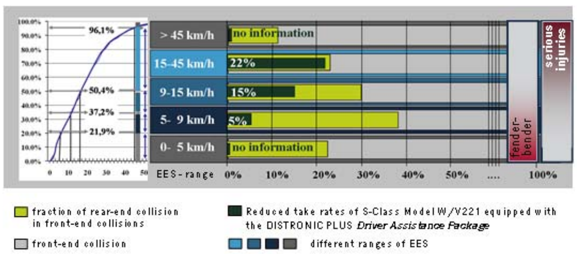

Fig. 11: Effectiveness in reducing front-rear accidents

In detail, the degree of efficiency is about 95% in the EES range [15 – 45 km/h], about 50% in the EES range [9–14 km/h] and about 13% in the EES range [5–9 km/h]. The degree of efficiency denotes the share of spare parts reduction attributed to the system's actions (assumed to be close to 100%, seeing that reference group and control group comprise same type vehicles) versus the computed share of front end damages attributed to rear-end crashes in this EES range (based on the above mentioned GIDAS analysis). The details are shown in Fig. 11.

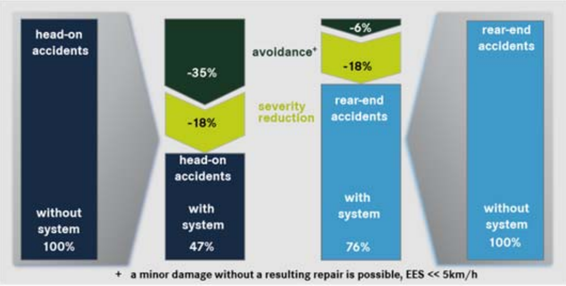

Fig. 12: Effectiveness in avoiding or mitigating the severity of rear-end collisions

This means that severity is shifted at least to the severity of the next (lower) severity range. It is interesting to note that the degree of efficiency is high where the severity of damage is high, i.e. where the speed difference of bullet and target vehicle is high. In other words, especially severe collisions were reduced in their severity.

As a secondary benefit, the calls of rear-end spare parts of the reference group that differ only in the mentioned equipment was also reduced significantly: Equipped vehicles show approximately 24% avoided or mitigated rear-end collisions compared to non-equipped vehicles (Fig.12).

It is assumed that the system has a positive side effect on following traffic prone to rear-end the subject vehicle: Due to the adaptive nature of BAS PLUS and early warnings by FCW, potentially late and hard panic reactions of following vehicle drivers may be changed to earlier, moderate reactions. This attenuating effect is especially helpful in multiple follow-up collisions, usually increasing in criticality because of cumulating late and more intense reactions.

The Adaptive Brake Assist component of CPA includes nearly all capabilities of BAS Plus with the exception of reacting on stationary vehicles that were never seen moving before (see Tab. 1). As stated previously it covers 82% of BAS Plus situations which results in 71% of all situations. Therefore this attenuating effect applies to CPA in a comparable magnitude.

A SPECIALITY: ACCIDENTOLOGY BASED ON SPARE PART CALLS

Effectiveness in avoiding **accidents** or mitigating their severity is **reflected** in the quantities ordered of **characteristic** spare parts.

A *unique* list of characteristic items/spare parts corresponds to a typical extant of a crashed vehicle – and vice versa. (Fig. 13)

Avoided accidents are reflected in reduced take rates. Mitigated severities are reflected in reduced length of orders. (A special spare part is missing in the order – different item list.) By adding "appropriate prior knowledge" –for example results from "classical" accident analysis or system characteristics to such an analysis, new connecting results can be established. This idea is demonstrated in two examples.

Fig. 13: Basic Idea of spare part call analysis: call corresponds to damage at a car

An elementary task of each accident research unit is to ascertain the impact energy and characteristic of real world crashes. Currently this is done in the accident research units within the OEM´s or in common comprehensive research projects like for example GIDAS in Germany. Both had the same disadvantage: due to their specific limitations they could not do it for a specific model range. However, the knowledge based approach of analysing spare part calls can do so. In this way an individual characteristic of the impact of *their* real world crashes and changes for example due to the use of primary safety measures could be analysed.

Fig. 14 showed the vertical location of the area of damage of a frontal crash. For the vehicles that were equipped with the *Driver Assistance Package* it moved to the lower region.

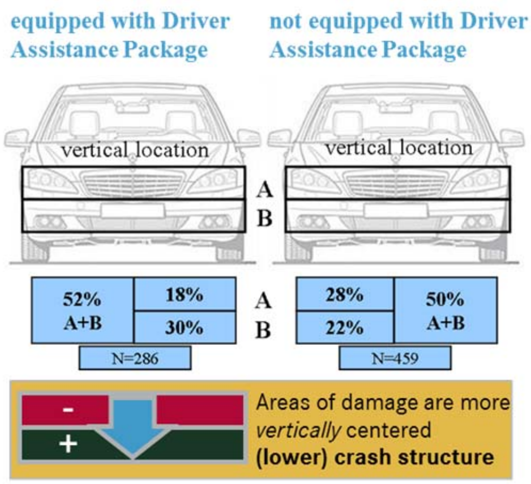

Fig. 14: Vertical damage regions of vehicles equipped and not equipped with the *Driver Assistance Package.*

Fig. 15 showed the horizontal location of the area of damage. Here the comparison of the results for the vehicles that were respectively were not equipped with the Driver Assistance Package showed that the vehicles that were equipped with the system had more overlap with their opponents. Both Fig. 14 and

Fig. 15 showed that the *Driver Assistance Package* leads to a more balanced energy input in the lower crash elements – bumper, cross member and so on.

Fig. 16 showed a comparison of the horizontal location of the impact area for frontal crashes with airbag activations. The differences are reduced overlaps at the right and left sides and an increased share of 100% overlapping.

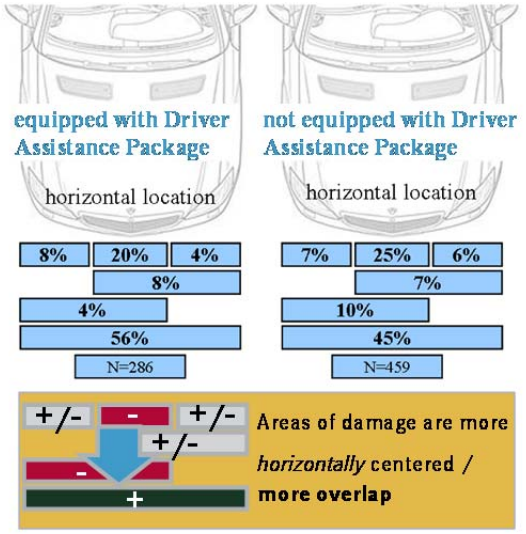

Fig. 15: Horizontal damage regions of vehicles equipped and not equipped with the *Driver Assistance Package.*

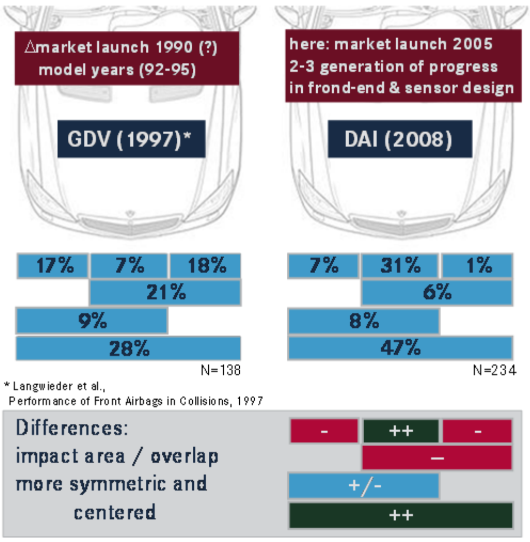

Figure 15: Overlapping of crashed vehicles with airbag activation – differences two studies with 10 years delay.

CASUALTY REDUCTION POTENTIAL BASED ON THE ANALYSIS OF SPARE PART CALLS

The findings are based on the comparison of spare parts calls for same type vehicles with and without DISTRONIC PLUS with FCW, BAS PLUS and PRE-SAFE® Brake stage 1.

To estimate the pertaining potential for casualty reduction, an Injury Risk Function (IRF) is applied to the results of the study [15]. This method is commonly used to estimate the benefit of primary or secondary safety measures. E.g., it was used to prove the equal effectiveness of BAS and secondary safety measures for Pedestrian Protection in [6] carried out for ACEA. For the purpose of this analysis, an injury risk function is required. The needed IRF describes the correlation between MAIS (Maximum Abbreviated Injury Scale) of the passengers of the striking car versus its Energy Equivalent Speed (EES) in a rear-end collision. This IRF was derived from the rear-end accidents contained in GIDAS 12-2008 database.

Two injury classifications were taken into account: slightly injured (MAIS=1) and at least seriously injured (MAIS>1). The class “fatally injured” corresponding to MAIS5+ contains too few entries (n=8). Therefore, only MAIS2+ was considered. Fig. 11 describes the correlation between injury risk (MAIS1+, MAIS2+) and EES.

The driver assistance safety features FCW, BAS PLUS and PRE-SAFE® Brake stage 1 within DISTRONIC PLUS influence the speed difference and thus the EES. This influence does not change the IRF, but the EES as its input. In a case-by-case analysis using the derived degrees of efficiency in the defined EES-ranges, the effect on EES can be predicted. The overall probability of MAIS1+ and MAIS2+ injuries decreases with the reduction of EES or collision speed.

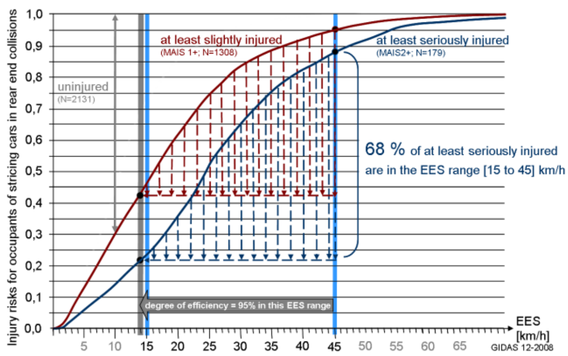

Fig. 16: Injury Risk Function for Bullet Car Occupants in Rear-End Collisions

Fig. 16 shows that about 68% of all at least seriously injured occupants of the striking car are contained in the EES range [15 – 45 km/h]. The degree of efficiency of the driver assistance functions FCW, BAS PLUS and PRE-SAFE® Brake stage 1 within DISTRONIC PLUS is 95% in this EES range.

The degree of efficiency denotes the share of spare parts reduction attributed to the system’s actions (assumed to be close to 100%, seeing that reference group and control group comprise same type vehicles) versus the computed share of front end damages attributed to rear-end crashes in this EES range (based on a GIDAS analysis).

Consequently, this system can reduce the damage level of collisions to at least below the lower limit of the EES range [15–45 km/h], i.e. EES=14km/h or less. Hence, the injury risk for all occupants that actually had an accident within the severity range from [15-45km/h] taken from GIDAS is reduced to the risk of the lower limit of the EES range. Or: The risk of a bullet car occupant of being "at least seriously injured" is reduced by the system from its former value (blue line in Fig. 16) to a new value (dotted blue line in Fig. 16). For each value of EES the downward arrows in Fig. 16 define the reduced injury risk. Adding up the number of occupants which were "at least seriously injured" in a collision with an certain value of EES for all values of EES out of the interval [15-45km/h] multiplied by their reduced risk results in the number of occupants that are no longer "at least severely injured" and so on.

Applying this to the case-by-case analysis yields the injury reduction benefit. The limitation to this EES range indirectly provides an elimination of collisions with initial / collision speeds of the striking car above 130km/h.

As a conservative approach, the system benefit is considered in the EES range [15 – 45 km/h] only. Additionally, it is assumed that the damage in this EES range is reduced to 14km/h EES for all cases (and not less).

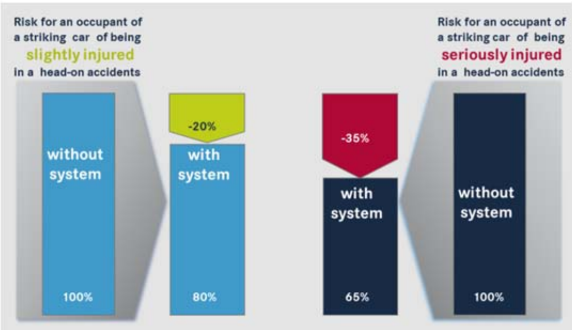

Fig. 17: Effectiveness in avoiding or mitigating the severity of injuries of an occupant of the striking car

Based on these assumptions, a mapping to real world accidents by leveraging a cumulative sum of EES frequencies leads to the following result: For this severity range the number of saved "at least seriously injured" occupants of the striking car is 63. 35 of these "at least serious injuries" were avoided, 28 were reduced to "slightly injured". Correlating this to the 179 at least seriously injured occupants (derived from GIDAS) yields an effectiveness of 35%.The results are shown in Fig. 17.

MEASURING SYSTEM REAL WORLD EFFECTIVENESS WITH INSURANCE DATA

National Umbrella organizations of insurance companies like the IIHS (Insurance Institute Highway Safety) and the HLDI (Highway Loss Data Institute) in the United States of America or the GDV (Gesamtverband der Deutschen Versicherungswirtschaft) in Germany usually have access to a big share of data of national automobile insurance claim data. Automobile insurance covers damages to vehicles and property as well as injuries to people involved in crashes. Depending on national law, some insurance coverages (including their details) are compulsory for every driver others are voluntary, different coverages may apply depending on who is at fault.

The automotive insurance data is representing the human and economic losses resulting from the ownership and operation of vehicles and the profit or loss that insurance companies gain from it. Consequently, the data covers a very high percentage (>80%) of all annual reported collision, that vehicles had on public roads and private properties. This is a good reflection of road accidents but the data also includes other collisions like low speed maneuvering collisions like parking. This representative large-scale insurance data usually contain data about the at-fault driver's vehicle and the involved vehicle that was damaged by it, cost in the category of the coverage and no/poor information about the details of the crash (for example point of impact, collision speed, type of crash …). A consequence of the missing detailed crash information is that effectiveness could not be measured against the use cases of the system for example front-to-rear-end crashes for forward collision warning system with collision mitigation braking functionality. Therefore, effectiveness measured with insurance data is always referring to ***all collisions*** regardless of the ability of a system to mitigate or prevent the crash.

Often active safety features are always bundled together on a vehicle and are not available individually. The bundled features vary between vehicle series and by model year. Thus often only the effectiveness of the bundle can be measured.

Another limitation is that the status of a feature is not known at the time of the crash. If a feature can be deactivated by the driver and there is no way to know how many, if any, of the drivers in these vehicles had manually turned off the system prior to the crash. If a significant number of drivers do turn these features off, any reported reductions may actually be underestimates of the true effectiveness of these systems.

General, studies based on insurance data should not be conducted too early. It should be ensured that the exposure rates with active safety features are not to small compared to the probability of accidents; (market introduction, take rates of optional equipment) to make sure that the stability of the results as well as their independence of special weather conditions, their use in correlation to road performance and mileage, the share of inter and extra urban rides are balanced.

Analyses of insurance collision claims are giving early indications of how crash avoidance technologies are working. In 2012 the HDLI [7] published a bulletin that summarized their findings on Mercedes-Benz collision avoidance features. Mercedes-Benz supplied HLDI with the identification numbers of those vehicles that had collision avoidance features, allowing HLDI to compare the insurance records for those vehicles with the same models without the feature. The study is based on property damage liability, collision, bodily injury liability, personal injury protection and medical payment coverages. The different insurance coverages are defined as follows:

- "Collision" pays for damage to the insured vehicle sustained in a crash with an object or other vehicle.
- "Property damage liability" (PDL) pays for damage an at-fault driver's vehicle does to other people's property as a result of a crash.
- "Bodily injury liability" pays for medical, hospital, and other expenses for injuries that at-fault drivers inflict on occupants of other vehicles or others on the road;
- "Medical payment" covers injuries to insured drivers and the passengers in their vehicles, but not injuries to people in other vehicles involved in the crash.

Insurance measures are:

- "Exposure", is expressed in insured vehicle years.
- "Claim frequency", is expressed as the number of claims per selected number of insured vehicle years (exposure).
- "Claim severity", represents the average cost per claim.
- "Overall losses", represents the average cost per insured vehicle (year), calculated by dividing total dollars paid for claims by exposure Insurance measures.

Vehicle damage coverage type	Collision	Property damage liability
Lower bound	-12,8%	-23,3%
Frequency	-7,1%	-14,3%
Upper bound	-1,0%	-4,2%
Lower bound	-$258	-$191
Severity	$145	$126
Upper bound	$578	$479
Lower bound	-$54	-$19
overall losses	-$18	-$8
Upper bound	$20	$40

Tab. 6: Changes in insurance losses in *vehicle damage coverage* for vehicles equipped with DISTRONIC PLUS (incl. Driver Assistance Package) [7]

The results of DISTRONIC PLUS incl. the *Driver Assistance Package* are contained in Tab. 6. There are reductions in the claim frequencies of *collision* of 7.1% and to a greater extend of 14.3% for PDL claim frequency of PDL. Reductions in loss claims are estimated for both first- and third-party vehicle damage coverages, resulting in somewhat lower losses per insured vehicle year (overall losses). Only the frequency reductions for collision and PDL were significant.

DISTRONIC PLUS incl. the *Driver Assistance Package* reduces the frequency of injury claims: -16% in bodily injury liability, -21% in medical payments and -15% in personal injury protection (payment for involved injured persons regardless of who's at fault in a collision). Under injury coverages, the frequency of paid and reserved claims is lower for all coverage types but none of the differences is statistically significant. Among paid claims, reductions are seen for all coverage types at both low and high severity (Fig. 7).

Vehicle damage coverage type	Collision	Property damage liability
Lower bound	-12,8%	-23,3%
Frequency	-7,1%	-14,3%
Upper bound	-1,0%	-4,2%
Lower bound	-$258	-$191
Severity	$145	$126
Upper bound	$578	$479
Lower bound	-$54	-$19
overall losses	-$18	-$8
Upper bound	$20	$40

Tab. 7: Changes in insurance losses in *injury coverage* for vehicles equipped with DISTRONIC PLUS (incl. Driver Assistance Package) [7]

As has been deduced before CPA could address 71% of all rear-end pre-crash situations these results are of considerable relevance to CPA.

COMPARISON OF DIFFERENT FOREWARD COLLISION AVOIDANCE SYSTEMS – REAL WORLD EFFECTIVENESS WITH INSURANCE DATA

Insurance data is suitable to compare the real world effectiveness of different systems. The claim frequency under property damage liability insurance, which covers damage to another vehicle caused by the insured vehicle, and collision insurance, which covers damage to the insured vehicle are able to compare the performance of different systems. The claim frequency under property damage liability insurance might be a more objective performance measure compared with the frequency of collision because it this measure is not so strong influence able by economic considerations on the extent of the future such as Insurance Premium.

HLDI analyzed the insurance claim data for FCW systems offered on Acura, Mercedes-Benz and Volvo. The results are displayed in Fig. 18.

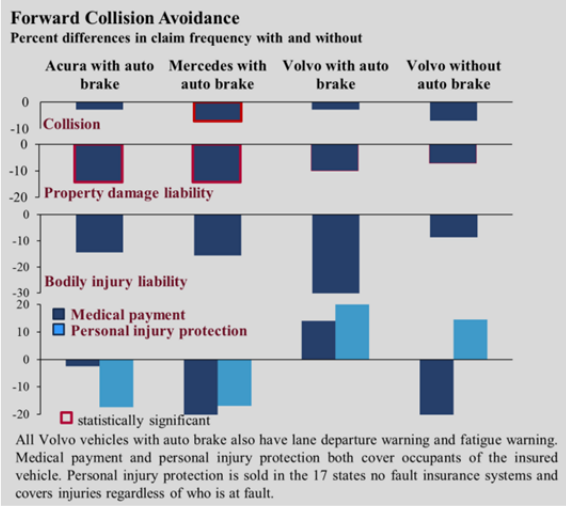

Fig. 18: Results of the HLDI analysis of insurance claim data [9]

The different systems under analysis had the following specifications:

"Acura with auto brake" means that the Acura were equipped with a Forward Collision Mitigation System that will provide visual and auditory warnings when speed and distance indicates a risk of a crash with the leading traffic and, if the driver does not respond by reducing speed, the system will tug at the seat belt to get the driver's attention and begin braking to mitigate — but probably not prevent — the crash. Collision mitigation becomes functional at speeds over 15 km/h and deactivates when speed drops below 15 km/h. It is bundled with an Adaptive Cruise Control system.

"Mercedes-Benz with auto brake" means that the vehicles were equipped with DISTRONIC PLUS in combination with the Driver Assistance Package (see Tab. 1) with the lower threshold of the operation speed rage of 30km/h.

"Volvo vehicles without auto brake" were equipped with Adaptive Cruise Control and Forward Collision Warning that uses radar sensors mounted in the front bumper to detect the risk of a collision. Driver warnings are both auditory and visual (red lights in a heads-up windshield display). If the driver brakes the warnings are canceled. The forward collision warning system is active only between speeds of 30 and 180 km/h. Vehicles with Forward Collision Warning also have Adaptive Cruise Control and Distance Alert.

"Volvo vehicles with Auto Brake" were equipped with a Forward Collision Warning system that includes some autonomous emergency braking. With Auto Brake, the system will also provide visual and auditory warnings when speed and distance indicate risk of a crash with the leading traffic and, if the driver's reaction does not eliminate that risk, the system will begin emergency braking to mitigate – but probably not prevent – the crash. Auto Brake becomes functional at speeds over 5 km/h and deactivates when speed drops below 5 km/h. Auto Brake operates whether or not Adaptive Cruise Control is activated. (All descriptions were taken from HLDI Bulletins.)

MEASURING SYSTEM REAL WORLD EFFECTIVENESS WITH ANNUAL REPORTED ROAD ACCIDENT DATA

The real world evaluation on the basis of federal accident statistics is the final step. Only here the true effectiveness of the safety measure can be verified.

Unfortunately, this step could not yet be performed. The S-class had not enough accidents in Germany for getting statistically significant results. All other models are not long enough on the market. An evaluation based on German accident figures is expected to be available in 2014/2015 for CPA.

CONCLUSIONS

The Real Life Safety evaluation circle (Fig. 2/19) is (nearly) closed for Mercedes-Benz Forward Collision Avoidance Systems. In each step a validation of a former report could be carried out.

Fig. 19: Evaluations made for the Mercedes-Benz systems: Driver Assistances Package consisting of: FCW, BAS PLUS, PRE-SAFE® Brake and Collision Prevention Assist

The Driver Assistance Package consisting of FCW, BAS PLUS, PRE-SAFE® Brake and Adaptive Brake that is available in combination with DISTRONIC PLUS showed in real world evaluations a high effectiveness in avoiding or mitigating the severity of rear-end collisions.

53% of all rear-end collision could be mitigated in their severity, from that 35% could be avoided.

The risk for an occupant of the striking car of being seriously injured is reduced by at least 35%.

Claim frequency reduced by 14.3% in the insurance coverage property damage liability.

It is important to note, that the Collision Prevention Assist CPA covers about 71% cases of the full

Driver Assistance Package consisting of FCW, BAS PLUS, PRE-SAFE® Brake and Adaptive Brake. Hence the effectiveness of the full package applies to CPA in a comparable magnitude.

ACKNOWLEDGEMENT

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A ONE YEAR PAY-AS-YOU-SPEED TRIAL WITH ECONOMIC INCENTIVES FOR NOT SPEEDING

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ABSTRACT

The objective was to identify if it was possible to change driver behaviour by economic incentives and thereby reducing crash risk. A one year Pay-As-You-Speed (PAYS) trial with economic incentives for keeping speed limits using Intelligent Speed Assistance (ISA) was therefore conducted in Sweden during 2011-2012. The full incentive was a 30% discount of the insurance premium. The participants were private insurance customers and they were randomized into a test group (initial n=152 and final n=128) and a control group (initial n=98 and final n=68). When driving the drivers in the test group were informed and warned visually when the speed limit was exceeded. They could also follow their driving results on a personal website. The control group was not given any feedback at all. For reflecting the impact of the PAYS concept the proportion of distance driven above the speed limit was compared between the two groups. The introduction of a PAYS concept shows that the test group significantly reduced the proportion of distance driven above the speed limit. The proportion of driving with a speed exceeding 5km/h over the speed limits was 6% for the test group and 14% for the control group. It also showed that the effect was higher the higher violation of speed. The result remained constant over time. A side effect of reducing speeding was that the fuel consumption was reduced and thereby the CO_2 emissions. The results show that a PAYS concept is an effective way to reduce speed violations. Hence, it has the possibility to reduce crash severity and thereby to save lives. This could be an important step towards a safer road transport system. The majority of the participants were in favour of the concept which indicates the potential of a new insurance product in the future.

INTRODUCTION

Speed has been identified as a key risk factor that has a powerful impact on the risk of sustaining a serious injury (Farmer and Lund 2006; Elvik 2007; WHO 2008). The biggest road safety problem in many countries is that road users exceed the speed limit (WHO 2008). For instance more than 50% of Swedish drivers violate posted speed limits (STA 2013). The correlation between speed and crashes or crashes with injuries has been described by power functions (Elvik et al. 2004; Nilsson 2004). Even small changes in average speed have a great effect on crash severity and thereby on risk of injury. A decrease in average speed of 5% is associated with a 15% reduction of sustaining a serious injury and a 20% reduction of fatalities.

Speeding is sometimes a result of an unintended error e.g. that the driver is adapting to a certain traffic situation (SWOV 2012). There are several technical solutions supporting the driver with how to keep the speed limit. ISA is a summary of systems that provide the driver with support on speed-control task. Euro NCAP will during 2013 implement a test protocol for ISA (EuroNCAP 2012). The systems will be rated regarding three different factors: communication, warning and limitation. There are several studies that indicate that ISA has a positive effect on driver behaviour regarding speeding (Almqvist and Nyård 1997; Hjälmdal 2004; Varhelyi et al. 2004). However, this effect decreases over time since the drivers tend to fall back to old driving behaviour (Wallen-Warner and Åberg 2008). Most studies evaluating ISA have been based on a voluntarily participation. Few studies have involved any rewards or penalties. A previous Swedish trial during three months with 114 participants has shown that ISA linked to economic incentives has higher impact on driver behaviour than ISA without (Hultkrantz and Lindberg 2011).

Insurance premium based on PAYS concept could be one way to stimulate safer driving by using ISA. In a previous Danish study with 153 participants, drivers were informed if the speed was exceeded and all speeding above 5 km/h was linked to penalty (Lahrmann et al. 2007; Lahrmann et al. 2012; Lahrmann et al. 2012). Beside the Danish study, few studies have been conducted based on PAYS concept linked to the speed limit. Some insurance concepts have used PAYS to investigate the speed in case of a crash but not during daily driving (Alka 2013). The objective with the present study was to identify if it was possible to change driver behaviour by economic incentives in terms of discount of insurance premium in correlation to real-time feedback of velocity driving and thereby reducing crash risk. Furthermore, the aim was to evaluate the participants attitudes to the participants attitudes to the PAYS concept.

METHOD

A one year trial with economic incentives for keeping speed limits using ISA was conducted in Sweden during 2011-2012. An enquiry was sent out either by a mail or by a telephone request to members of a major Swedish motor club, Motorförarnas Helnykterhetsförbund (MHF). The inclusion criteria were that the members of the motor club were private insurance customers in Folksam Insurance Group and that they were between 22 and 66 years of age. The participants were randomized into a test group and a control group (see Table 1). When driving the drivers in the test group were informed and warned visually when the speed limit was exceeded. They could also follow their driving results on a personal website. The full incentive was a 30% discount of the insurance premium for the participants in the test group. The discount was depending on the amount of speeding. The control group was not given any feedback at all during the trial and got a 20% discount regardless of their driving behaviour. To analyze the effect of the PAYS concept the proportion of distance driven above the speed limit was compared between the two groups. Questionnaires were sent out to the participants before, during and after the trial asking questions concerning for instance acceptance and usability. The participants in the control group just got questionnaires before and after the trial.

Dropouts

There is a total dropout of 24 participants from the test group and 30 participants from the control group. Already before the device was mounted into the vehicle, 8 participants (7 from the test group/1 from control group) chose to leave the trial. The most common reason for a dropout was that the participant chose to change insurance company while the trial was running (14 from the test group/17 from control group). Another reason was technical malfunction of the system (12 from control group). Only three in the test group had other reasons for leaving the trial. The dropouts were spread out during the whole test period.

The ISA system

The ISA system was based on a GPS receiver that continuously identified the position of the vehicle. The ISA system was also linked to a digital map in the National Road Database including speed limits of the Swedish national road network. The measured speed by the GPS was compared to the posted speed limits according to the digital map, and speeding could be detected and recorded. A display containing the whole system was mounted on the dashboard in all cars. When driving, the drivers in the test group were informed about driving velocity in relation to current speed limit. On the display the current speed limit was continuously shown as well as a coloured circle that changed colour depending on if the driver was speeding or not (See Figure 1). If the driver exceeded the speed limit it turned from green to yellow and if the driver exceeded the speed limit with more than 5 km/h the circle turn red. The system was automatically activated when the engine was started. The proportion of speeding was calculated by accumulating all driving data during a ride. Maximum 30% reduction of the insurance premium was given to drivers with less than 1% of the distance driven over the speed limit. The control group had no display and therefore no feedback of driving behaviour during real-time or by website was given.

Table 1.
Participants characteristics

Group	N	Mean age	Median	Min. age	Max. age	5:e percentile	95:e percentile	Gender Female/ Male (%)
Initial participants								
Test group	152	50	51	26	79*	30	65	23/77
Control group	98	58	59	26	66	40	65	37/63
Participants with measured data month 1 and month 11								
Test group Month1-11	121	51	52	26	79*	31	66	21/79
Control group month 1-11	65	58	59	26	66	41	66	48/52

*One participant in the test group did not fulfil the inclusion criteria (age 22-66)

Figure 1. The ISA system mounted on the dashboard in all participants' cars included in the test group

Analysis of vehicle data

The on-board ISA system recorded data at 1 Hz. Data used for analysis was distance-based. The variables measured during driving were distances driven, average speed and distance driven above the speed limit split in three categories; 1-5 km/h above the speed limit, 6-10 km/h above and 10 km/h above or higher.

Statistical analysis

To reflect the effect of PAYS concept, the total proportion of distance driven 6 km/h or more above the speed limit was compared between the two groups and used to describe the change in speed behaviour. Even differences within the group as well as individual level were studied. The first month was used as baseline to study differences over time. In this analysis only participants with measured driving data month 1 to month 11 was used (See Table 1). Furthermore, distributions of speeding as well as differences in average speed between the two groups were studied for different speed limits. Difference in travel time was calculated based on average speed and average mileage driven (13,000 km/year). In analysis regarding average speed weighted mean speed was used. For comparative purposes also mileages, age and gender distribution were checked.

To investigate the difference between those in the test group and those in control group that drove the fastest, the 85 percentiles was used. Non-parametric confidence intervals were used for the percentiles and the software Scientific Workplace 5.5 was used for the calculation. In all the other analyses, 95% confidence interval were used, and p-values from t-tests was calculated using SPSS software (PASW 20).

RESULTS

The evaluation of the PAYS concept showed that the test group significantly reduced the proportion of distance driven above the speed limit (See Table 2). The proportion "red" driving (6 km/or more above the speed limit) was 6% for the test group and 14% for the control group. Regardless speed limit, the control group had a larger proportion of distance driven 6 km/h or more above the speed limit (See Figure 2). The distribution of speeding was also analysed, the effect was higher the higher violation of speed. The reduced speeding in the test group did not have any large effect on the average speed compared to the control group (see Table 3). The test group had less than 1.5 minute longer travel time per hour travelled.

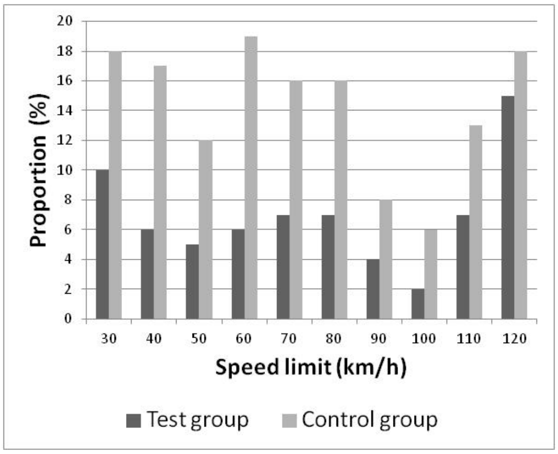

Figure 2. The total proportion of distance driven 6 km/h or more above the speed limit

The speed distributions differ between the two groups (See Figure 3-6). The impact of PAYS concept could be studied by looking at the shape of the speed distribution. Figure 3-6 show the most common speed limits in Sweden but the same pattern was seen at all speed limits. A high proportion is below the speed limit which also was reflected in the average speed. The difference between the two groups was less on roads with a speed limit of 70 km/h.

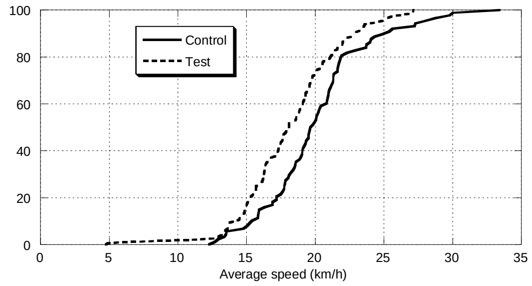

Figure 3. Speed distribution on roads with a speed limit of 30km/h

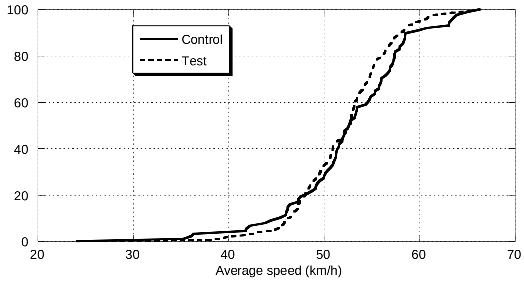

Figure 5. Speed distribution on roads with a speed limit of 70km/h

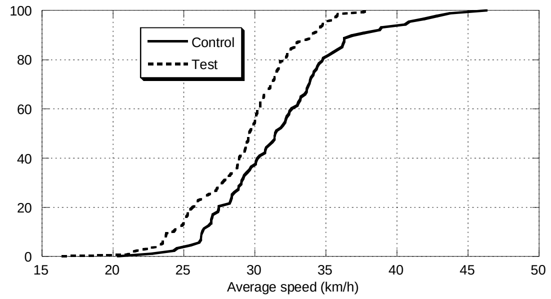

Figure 4. Speed distribution on roads with a speed limit of 50km/h

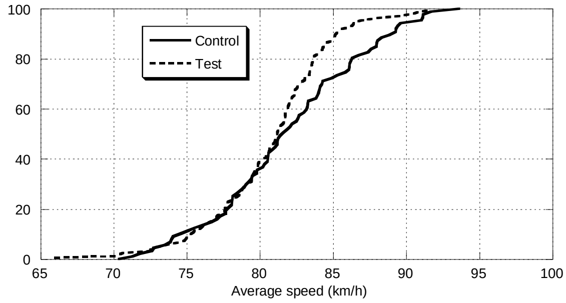

Figure 6. Speed distribution on roads with a speed limit of 90km/h

Table 2.
Total distance (km) and distance driven above the speed limit for both the test group and control group

Group	Total distance (km)	Distance 0-5km/h over speed limit (km)	Distance 6-10km/h over speed limit (km)	Distance 11-20km/h over speed limit (km)	Distance above 20km/h over speed limit (km)
Test group	1767150	162688 (9.2%)	52144 (3.0%)	44057 (2.5%)	14180 (0.8%)
Control group	1015284	120394 (11.9%)	67448 (6.6%)	55999 (5.5%)	20315 (2.0%)

Table. 3
Differences in average speed between the test group and control group on roads with different speed limits

	30 km/h	40 km/h	50 km/h	60 km/h	70 km/h	80 km/h	90 km/h	100 km/h	110 km/h	120 km/h
Average speed										
Test	18.15	26.90	29.81	48.44	52.10	73.65	81.52	88.59	101.07	111.43
Control	19.99	26.50	31.27	49.59	53.06	74.92	82.43	89.55	101.74	111.25
Diff.	1.84	-0.40	1.46	1.15	0.96	1.27	0.91	0.96	0.67	-0.18
CI	±0.058	±0.050	±0.005	±0.039	±0.010	±0.030	±0.015	±0.028	±0.13	±0.13
Average speed while speeding										
Test	37.54	46.21	56.17	65.69	76.67	87.48	97.11	106.77	117.20	128.70
Control	38.34	48.40	57.81	69.75	79.45	88.39	98.65	107.62	118.14	127.79
Diff.	0.80	2.19	1.64	4.06	2.78	0.91	1.54	0.85	0.94	-0.91
CI	±0.006	± 0.031	±0.004	±0.027	±0.012	±0.051	±0.049	±0.058	±0.057	±0.28

The study shows that the effect of PAYS concept is constant after eleven months, both on group level and individual level. However, within the test group there was a tendency to increase their proportion of speeding on an individual level. The proportion of speeding increased with 2% (CI 0.4-3.7) (See Table 4).

Table 4.
Changes in proportion of speeding on individual level, the first month used as baseline.

Month	Average (%)	CI
June-July	-0.0037	-0.0121 – 0.0046
June-Aug	-0.0086	-0.0167 – -0.0005*
June-Sep	-0.0118	-0.0230 – -0.0007*
June-Oct	-0.0059	-0.0153 – 0.0034
June-Nov	-0.0075	-0.0204 – 0.0054
June-Dec	0.0009	-0.0078 – 0.0095
June-Jan	0.0058	-0.0049 – 0.0165
June-Feb	-0.0009	-0.0120 – 0.0103
June-Mars	-0.0112	-0.0246 – 0.0022
June-April	-0.0203	-0.0366 – -0.0040*

* significant difference

Individual level of speeding

The test group had a lower proportion of speeding on individual level than the control group. By studying the proportion of distance driven 6 km/h or more above the speed limit on an individual level it was found that more than 40% of the drivers in the test group drove less than 1% of the total distance above the speed limit. The corresponding figure for the control group was approximately 10%. By studying the difference between those in the test group and those in control group that drove the fastest it was found that it was a great difference between the two groups. The 85^{th} percentiles for the test group was 8.8 % (CI: 0.0513–0.1826) and 25.3 % (CI: 0.221–0.443) for the control group. The corresponding figure for the 15^{th} percentiles was 0.2 % (CI: 0.0018–0.0061) for the test group and 1.2 % (CI: 0.0033–0.0296) for the control group. The speed distribution in the test group was thereby lower than in the control group.

A side effect of reduced speeding was reduced fuel consumption and thereby reduced emissions. The calculated average reduction was approximately 300 kg CO_2 per year and driver. The lowered fuel consumption corresponds to an average lowered fuel cost of EUR 200 per driver each year. The average premium discount for the test group was 21%, corresponding to EUR 100 per driver per year in Sweden. The total saving was approximately EUR 300 for each driver per year.

Based on the questionnaires nine out of ten think that the tested PAYS concept was an effective tool to keep speed limits. Few saw it as an integrity threat. Eight percent thought that their “freedom” was narrowed. In total 75% of the participants in the test group would be interested in an insurance product of this kind.

DISCUSSION

The results show that a PAYS concept is an effective way to reduce speed violations. Hence, it has the possibility to reduce crash severity and thereby reduce the risk of injuries and fatalities. Reducing speed will have a positive impact on both vehicle occupants and vulnerable road users. By applying established correlations such as the power model (Elvik et al. 2004; Vadeby and Forsman 2012) the reduced speeding in the test group could be correlated to a reduced fatality risk by 20% and a reduced risk of serious injury by 5-10% if all drivers in Sweden were using the system. This is in line with the result of a study conducted by Lai et al (2012) that have predicted ISA to reduce the fatal accidents by 30% and serious accidents by 25% of over a 60-years period. This shows that PAYS concept could be an important step towards a safer road transport system. The majority of the participants were in favour of the concept (9 out of 10) which indicates the potential of a new insurance product in the future.

Road users exceeding the speed limit is a major road safety problem (WHO 2008). It is known that ISA has a positive impact on driver behaviour regarding speeding (Almqvist and Nyård 1997; Hjälmdal 2004; Varhelyi et al. 2004). However, Wallén-Warner and Åberg (2008) have shown that ISA only has a temporary effect since the drivers tend to fall back to old driving behaviour after a couple of month. Previous studies have mainly been based on a system without any benefits for the driver. The present study, as well a previous study of Hultkrantz and Lindberg (2011), shows that the effect of ISA is greater if it involves some kind reward or penalty. Furthermore, it indicates that the rewards in the present study encourage the participants to maintain a low proportion of speeding, as the effect was constant during the one year test period.

There are mainly benefits associated with the PAYS concept such as increased safety and lower emissions. The purpose of PAYS concept is to prevent drivers from speeding rather than reducing speed in general. The average speed was fairly similar between the two groups. The fact that there was no major difference regarding average speed will increase the customer acceptance. In average the premium discount was 21% which corresponds to approximately 100 annually. Beside this, a participant in the study saved an average of 200 in fuel cost annually based on general average fuel consumption. A PAYS concept must make economic sense to consumers otherwise they will not sign up for this type of insurance concept. Both insurance companies and the society will gain on PAYS concepts since customers are changing behaviours that directly relate to crashes and injury risks. So there is a high potential benefit for the whole society to save lives and costs.

Redefining insurance through dynamic risk

Today car insurance costumers only have small possibilities to influence their premium. Traditionally it has been common to differentiate insurance premiums for gender, age and residential address, which have no direct relationship to individual driving behaviour. The Court of Justice of the European Communities has since late 2012 prohibited differentiation of insurance premiums for gender (EuropeanCommission 2012). It is therefore important to create a premium setting that includes gender equality. The PAYS concept, proposed and evaluated in the present study, could be one way to create a more efficient and equitable vehicle insurance product. Factors involving driving behaviour will be a better way to predict risk than historical rating variables. Furthermore, this type of driving data can be integrated with traditional vehicle insurance rating factors to provide a more comprehensive individual customer profile for predicting the risk of accidents. Considering the high effectiveness found and the positive customer responses, it is recommended that insurance companies further introduce PAYS concepts.

Car insurance premiums based on actual driving behaviour have become both technologically and economically feasible during the last couple of years. Today most of the products on the market are mainly based on Pay-As-You-Drive, which can e.g. include mileage, acceleration and time of day, possibility to track the vehicle (e.g. Unipol Gruppo Finanziario and The Coperative Insurance). However, these are mainly to prevent theft and fraud and to lower the mileage driven. Some of these variables could also have a good effect of speeding, however one main aim for many insurance companies is to prevent theft and frauds since it is a substantial problem in many countries. Only a few Pay-As-You-Drive concepts are based on speeding even if speed has been identified as a key risk factor that has a powerful impact on the risk of crashes/crashes with injuries. The fact that Euro NCAP will, during 2013, implement a test protocol for ISA (EuroNCAP 2012), means that the basic platform for Pay-As-you-Speed techniques will be available in most vehicles within a short time frame. This will also improve the development of this kind of system and decrease the cost of producing and running such devices.

The Pay-As-You-Drive concept will be attractive to those customers who want more control over their insurance costs, those customers who has environmental concerns and those who desire real-time feedback in the vehicle. Furthermore, this system could also be used to track and to give information about traffic congestions.

Limitations

The participants in the test and control groups have voluntarily accepted to install speed-alert devices. This indicates that they are more inclined towards safe driving than the general population. However, the difference between the case and control groups should not be influenced by this. The impact of the system might be even higher for other part of the population.

The study group consisted of over 200 private insurance customers who all shared their driving data during one year trial. The primary hypothesis was that the PAYS concept would impact the driving behaviour. Furthermore, the objective was also to study if the impact was constant over time since a large majority of studies conducted to evaluate ISA have been limited in time. The present study is based on a one year trial and the result was constant over time. However, on an individual level the participants tend to increase the proportion of speeding with 2%. It is known that drivers tend to fall back to old driving behaviour (Wallen-Warner and Åberg 2008). It is therefore important to study driver behaviour after long-term use of PAYS concept to evaluate if impact of this type of system might change over time.

The present study is in some way unique. Few countries have a digital road map that includes the speed limits of the whole national road network. This fact makes it difficult to run a large scale trial to evaluate this type of system. Previous studies have therefore only included small parts of the road network and some selected roads with different speed limits . However, the technology in new cars can recognise and read speed limit signs to give information about local speed limits. This opens up for new technological solutions and to new large scale trials.

Digital maps will always have some problems regarding accuracy of the position of the speed signs and the speed limit itself, although continuous improvements will take place as the PAYS insurance product develops and is running. In this study drivers detecting errors could report this via the PAYS device directly to the responsible body for the digital maps. The error that the drivers were most critical to was changes from one speed limit to another. To reduce the influence of such errors certain buffer distances or time periods could be introduced. In order to create an insurance solution it is important to further discuss the question of responsibility regarding the accuracy of the digital maps.

CONCLUSIONS

The results show that a Pay-As-You-Speed concept is an effective way to reduce speed violations. By comparing the test group to the control group a more than 50% reduction of speeding was discovered. Furthermore, the higher speeding, the higher difference between the two groups. That means that the concept has the greatest impact on excessive speeding. Hence, it has the possibility to reduce crash severity and thereby to save lives which is an important step towards a safer road transport system. The majority of the participants were in favour of the concept which suggests a great potential of an insurance product.

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EDR PRE-CRASH DATA: POTENTIAL FOR APPLICATIONS IN ACTIVE SAFETY TESTING

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ABSTRACT

Passive safety testing has been based on accident research where objective physical evidence can be compiled and analysed when establishing technical test requirements. Active safety tests pose new challenges because objective data is more difficult to obtain. Until pre-crash variables became available in Event Data Recorders (EDR), the only sources of pre-crash vehicle motions were tire marks or witness statements. Both data sources have limitations since they may not always be available and require interpretation by the analyst. The pre-crash EDR data variables provide an objective source of data to active safety test development. However, the suitability of the data has not been thoroughly investigated in the published literature.

The review of existing data shows that the variables identified in the new EDR requirement in FMVSS 563 are useful but incomplete for a comprehensive analysis of vehicle dynamics manoeuvres prior to a crash. In particular, the absence of vehicle yaw rate reduces the positioning accuracy of the vehicle in reconstructions. The objective data in the limited cases were used to compile the frequency of pre-crash braking and steering, and when possible, the magnitude of these driver inputs.

Active Safety test development will benefit with more EDR analysis but the older data that does not conform to Part 563 has limited application.

INTRODUCTION

Vehicle manufacturers have been offering newer or improved driver support features that can increase safety to the occupant. Adaptive Cruise Control and Lane Departure Warnings systems are examples of systems that increase comfort and safety during driving because the vehicle is able to monitor its position relative to the other vehicles (ACC) or the road (LDW). Technological developments have led to more autonomous systems that not only warn the driver, but may even initiate autonomous interventions. The most notable example is the Automatic (or Autonomous) Emergency Braking systems that are now offered as standard equipment on several vehicle models some passenger vehicles [1]. These systems intervene with the driving process and apply the brakes under predetermined conditions. Corresponding functions are being developed for the steering system as electric power steering facilitates the possibility for automatic steering corrections.

There are many issues that need to be resolved before autonomous functions take over significant periods in the driving task. The current trend is to activate a function when a collision is unavoidable, thus limiting the liability issues that arise. Issues related to the responsibility of the driver and liability for actions of autonomous systems are beyond the scope of the reported study. There is, however, a critical need to identify conditions for activation and the amount (magnitude and duration) of system intervention during safety critical events. Both regulatory and consumer testing programs are being prepared. For example heavy vehicles in Europe will be required to be fitted with AEB to comply with a new ECE Regulation [2]. EuroNCAP is now crediting vehicles AEB and will begin testing AEB systems in 2014 [3]. NHTSA has proposed test protocols for Dynamic Brake Support [4] and Collision Imminent Braking [5] that were published for comments in 2012.

Research efforts to define test protocols and performance criteria have increased considerably in the last years. The European Commission funded activities include the recently completed “ASSESS[6]” project and the ongoing ASSpeCCS[7] project that address car-to-car and car-to-pedestian safety issues including pre-crash assessments. Smaller scale projects have been initiated with different groupings of project partners such as the AEB Test Group [8]. Similar activities have been reported in the US with NHTSA being a focal point for the project reporting. Large scale research programs like Advanced Crash Avoidance

Technologies (ACAT) sponsored by NHTSA [9] have focused on specific countermeasures and evaluation methodologies while naturalistic driving studies such SHRP2[10] have been directed at fundamental data collection to investigate driver-vehicle-infrastructure interactions.

Test methods for assessing active safety systems to avoid or reduce the severity of a crash must address the following points:

- Scenario for evaluation
- Facility and equipment
- Assessment criteria

The first point, the traffic scenario, is critical for the subsequent development of the test protocol. A scenario addresses the pre-crash orientation of the traffic elements, type of road users involved, and outlines the needs of the system under of evaluation. The development of the scenario thus needs information on safety critical events to both identify the frequency and outcomes of different incidents as well as the specific information describing the actual sequence of events. The current trend in active safety test development is to develop forgiving targets that vehicle sensor systems will perceive as cars or pedestrians. The surrogates must move like their real life counterparts and part of the challenge for the test development is to identify how fast a target should move in terms of absolute speed and speed relative to the tested vehicle. EDR data contains both information relevant for defining test speeds for the vehicle under investigation, as well as the positioning requirements for test targets or other test infrastructure.

Identifying and prioritising scenarios has evolved from the analysis material and procedures applied in occupant protection, or passive safety, research. The existing crash databases contain information outlining the type of collisions and the environment surrounding the crash. The focus in this research has been the analysis of the crash severity and injury outcome. Analytical assessment tools in accident reconstruction provide the majority of this information in databases such as NASS[11], GIDAS[12], CCIS[13], etc. Event Data Recorders (EDR) or Crash Recorders have complemented the knowledge on crash severity by recording vehicle motions during the crash for those vehicles equipped with a recording system. A review of EDR systems and analysis of data gathered up to 2005 is documented by de Silva [14]. NHTSA has now imposed a requirement that after September 2012, all vehicles equipped with an EDR shall supply a minimum set of data elements according to Code of Federal Regulation Part 563 [15], including data prior to the impact.

The quality of analytically reconstructed crashes is suitable for detailing some of the pre-crash conditions that are needed to develop a test protocol. This data is not as reliable when it comes to addressing the timing of pre-crash inputs from the driver such as braking and steering, that may influence the performance of a system and be crucial in its evaluation. EDR data provides a direct record of variables such as vehicle speed allowing the potential to investigate the prevalence and relevance of driver actions recorded during a crash.

OBJECTIVES

The study investigates the availability and suitability of EDR that is available from the NASS data gathering program. The type of data, variation of data within the vehicle fleet, and its applicability to developing active safety test protocols will be assessed. The sensitivity of data elements will also be explored to identify the reliability of EDR outputs when applied to active safety test development. The study focuses on the analysis of EDR data related to the most mature active safety testing procedure which is rear end impacts.

METHODS AND DATA SOURCES

The data investigated in this study primarily comes from the EDR files collected in the NASS data activities. This data is publicly available and the data connected with the NASS Crashworthiness Data System cases which are well documented by the case investigators.

EDR OVERVIEW

The details of EDR systems and the associated data are well described on the NHTSA EDR website [16] and [14]. In short, EDRs consist of a computer memory that is connected to the vehicle supplemental restraint system (SRS). The system continuously logs data but only activates permanent storage when the restraint system deployment algorithms “wake up”. Depending on the violence of the event, the system logs the event as a “deployment” or “non-deployment” if any of the restraint system components such airbags or seatbelt pre-tensioners deploy. Most EDRs store the two most recent events.

Until Part 563 came into place, there were no requirements for manufacturers to have harmonised variable and recording formats. One working group, IEEE 1616[17], defined output protocols in 2004 but the actual data elements had not been defined until NHTSA implemented Part 563. Most of the EDR data was focused on passive safety information such as crash pulse and airbag deployment times and pre-crash data was limited, if not absent, in the first EDRs introduced before the year 2000. Part 563 stipulates the minimum data elements, recording intervals, and data formats for EDR systems. This does not preclude the manufacturer from supplementing Part 563 with richer storage protocols. Table 1 provides the minimum data specifications for Part 563. Suggestions for additional data elements are also provided.

Table 1 – Data Elements Required for All Vehicles Equipped with an EDR[15]

Data Element	Recording Interval/Time[1] (Relative to time zero)	Data Sample Rate Samples per Second
Delta-V, longitudinal	0 to 250 ms	100
Maximum delta-V, longitudinal	0-300 ms	n.a.
Time, maximum delta-V	0-300 ms	n.a.
Speed, vehicle indicated	-5.0 to 0 sec	2
Engine throttle, % full (or accelerator pedal, % full)	-5.0 to 0 sec	2
Service brake, on/off	-5.0 to 0 sec	2
Ignition cycle, crash	-1.0 sec	n.a.
Ignition cycle, download	At time of download	n.a.
Safety belt status, driver	-1.0 sec	n.a.
Frontal air bag warning lamp, on/off	-1.0 sec	n.a.
Frontal air bag deployment, time to deploy, in the case of a single stage air bag, or time to first stage deployment, in the case of a multi-stage air bag, driver	Event	n.a.
Frontal air bag deployment, time to deploy, in the case of a single stage air bag, or time to first stage deployment, in the case of a multi-stage air bag, right front passenger	Event	n.a.
Multi-event, number of events (1,2)	Event	n.a
Time from event 1 to 2	As needed	n.a.
Complete file recorded (yes, no)	Following other data	n.a.

[1]Pre-crash data and crash data are asynchronous. The sample time accuracy requirement for pre-crash time is –0.1 to 1.0 sec (*e.g.*, T = -1 would need to occur between –1.1 and 0 seconds.)

DATA REVIEWED

To investigate the utility of EDR data for active safety test development, the EDR data for NASS year 2009 was downloaded from the NHTSA website. At the time of writing, this was the most recent data set available for a full calendar year. NASS EDR data for 2010 and 2011 have been recently uploaded but has not been incorporated herein. A total of 690 EDR reports were retrieved by NASS investigators. Of these cases, 291 had reported a deployment of the SRS and 339 had no deployments. Fortunately the EDR will still save data with an event that initiates an algorithm “wake-up”.

The EDR data was grouped into different collision categories to identify the distribution of incidents relative to the priorities for active safety test methods under development. Data from different cases were reviewed to see if the EDR records contained relevant data for the analysis.

An important piece of information in Table 1 is the note about the pre-crash and crash data timing. The data is asynchronous for the pre-crash and crash sequences and a 1 second uncertainty can exist.

Further analysis was done with a reconstruction of a case to identify how well the recommendation reflects the needs for test protocol developments. This reconstruction was conducted using simplified vehicle dynamic models programmed in Matlab using the pre-crash data elements stored in the EDR.

RESULTS

NASS has a variable for accident type (ACCTYPE) in the NASS General Vehicle dataset. The variable describes the vehicle manoeuvre at the time of the crash and is the most relevant parameter for use in the analysis described here. The ACCTYPE variable has 6 main categories identifying single vehicle collisions, rear end collisions, etc. The categories contain subgroups (e.g. depart road left, depart right) and the subgroups contain a number of specific accident types. There are 13 subgroups and 93 accident type codes[18]. Table 2 shows the frequency and proportion of crashes with EDR records.

The 3 most common type of collisions were: Changing Trafficway, Vehicle Turning (turning conflicts); Single Vehicle; and Same Trafficway, Same Direction (i.e. rear end crashes). If the accidents are broken down into each crash type where an active safety system would have reduced or eliminated the consequences of a crash then the 15 most common types are presented in Table 3.

The distribution of model years captured in the data sample is shown in Figure 1. The plot shows the relatively even distribution of cases over the interval 2001-2008. This reflects the penetration of EDR equipped vehicles in the fleet. The oldest vehicles in the sample are GM. The oldest Ford case is a 2001 year model with the oldest Chrysler being a 2004 year model. No other manufacturers were identified in the 2009 sample.

Table 3: Proportion of EDR cases for each NASS Accident Type Category

Collision Type	*Frequency*	*Proportion*
68 Initial Opposite Directions (Left/Right)	52	8.3%
69 Initial Opposite Directions (Going Straight) Directions (Going Straight)	48	7.6%
2 Control/Traction Loss	44	7.0%
20 Stopped	36	5.7%
7 Control/Traction Loss	33	5.2%
83 Turn Into Opposite Directions (Going Straight)	31	4.9%
1 Drive Off Road	29	4.6%
86 Striking from the Right	23	3.7%
88 Striking from the Left	21	3.3%
6 Drive Off Road	14	2.2%
28 Decelerating (Slowing), Gowing Right	12	1.9%
50 Lateral Move (Left/Right)	10	1.6%
51 Lateral Move (Going Straight)	10	1.6%
65 Lateral Move (Going Straight)	10	1.6%
13 Pedestrian/Animal	9	1.4%
Total	382	60.6%

Figure 1: Distribution of Model Year in the 2009 EDR Database

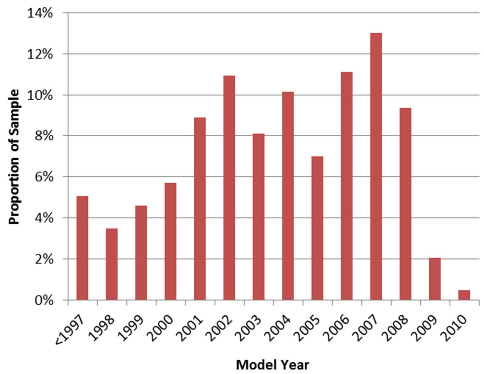

Figure 1: Distribution of Vehicle Model Years Sampled in the 2009 NASS Dataset with EDR Data

Relevant Cases for Active Safety Testing

Several initiatives to develop active safety tests have been identified and the common themes have been rear end and pedestrian collisions. As seen in Tables 1 and 2, these are relevant but are not the most common according to the sample, being the third most common event type.

Impacts with stationary or objects travelling in the same direction as the subject vehicle are among the easiest collision types to address with automated systems. Rear end impacts are a relatively simple event for vehicle sensors to monitor compared to events where threats cross the path of the vehicle. Cameras, radar, and other detection systems have the greatest effectiveness when looking forward so that the vehicle's path is monitored. Current technologies have a limited field of view and the ability for a threat detection algorithm to be effective depends on the length of time the potential

Table 2: Proportion of EDR cases for each NASS Accident Type Category

Category	*Frequency*	*Proportion*
IV: Changing Trafficway,	189	30.0%
I Single Vehicle	153	24.3%
II Same Carriageway, Same direction	124	19.7%
V: Intersecting Paths (Vehicle Damage)	77	12.2%
VI: Miscellaneous	48	7.6%
III: Same Trafficway,	37	5.9%
Uncoded	2	0.3%
Total	630	100%

threat is in the sensor's field of view. The fact that rear end impacts are amenable to active safety countermeasures makes these collisions relevant for analysis of EDR data availability.

Single vehicle collisions are the second most frequent group of collisions in terms of EDR data availability. Many of the cases identified in the dataset involve loss of control conditions. As this collision type is addressed by ESC systems, further investigation is not pursued in this analysis but is recommended for further development, particularly in combination with the other single vehicle collisions that could benefit from lane keeping and lane departure warning systems.

The most common collision type was where approaching vehicles cross paths due to intersection or other lane departure manoeuvres. Although lane departure waning is not pursued in this study, the applicability of EDR data to approaching vehicles is studied to get an understanding of the sensitivity of EDR data elements.

Rear End Impacts

There are a number of test methods proposed for detecting stopped or slower moving vehicles in the subject vehicle's path. Relevant inputs to these tests are the speed of the vehicles and the lateral orientation of the vehicles prior to impact.

The EDR dataset contains no positioning information prior to impact. For vehicles complying with the Part 563 protocol, steering wheel angle should be reported. All the 2009 cases reviewed contained no steering wheel information other than one case with a steering wheel angle of 0 deg. Although the database does contain vehicles with pre-crash steering information, none were involved in this particular crash configuration or had any steering input prior to the crash.

Vehicle speed prior to the impact is relevant to identify both the initial speed of the vehicle and the driver actions up to the point of impact. Figure 2 shows brake application (off - on) prior to impact. There is no obvious trend for the limited cases analysed but one can notice that there is tendency for brake application in the last 3 seconds prior to the crash. daSilva reported that brake application in rear end crashes was observed mostly in the last 3 seconds prior to collision, but still only 50% of striking had active braking in the last second before impact [14].

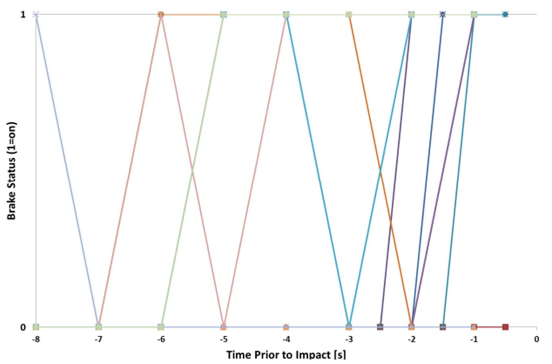

Figure 2: Brake Switch Status Prior to Crash in Rear End Collisions

Figure 3 shows a selection of pre-crash speed prior to the impact. As one would expect, there is a large amount of scatter with impact speeds up to 105 km/h being recorded. This reflects the range of accident locations where rear-end crashes can occur, spanning high speed motorways and low speed urban settings. The majority of pre-impact speeds are between 30 and 80 km/h in the last 3 seconds prior to impact, and is agreement with current test proposals [4,5,6,8].

The data in Figures 2 and 3 only reflect the following, or striking vehicle. It is important to not only consider the absolute speed, but even the relative speed between vehicles. The database contains many cases where an EDR recorded the struck vehicle speed and not the striking vehicle. This information is useful for evaluating the status of a vehicle target in a test procedure. One case was available with EDR data in both vehicles. The speeds of the two vehicles are shown in Figure 4. The struck vehicle was decelerating while the striking vehicle accelerated in the 5 seconds recorded prior to the crash. The relative velocity at the time of impact was approximately 50 km/h, based on the EDR time base. The struck vehicle was coded as stationary vehicle – while the EDR data demonstrates that the collision type was better represented as a decelerating vehicle.

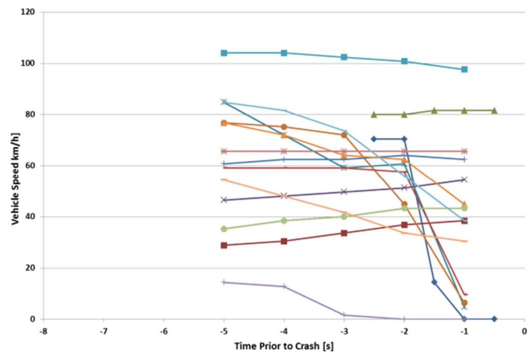

Figure 3: Vehicle Speed Prior to Rear End Crashes

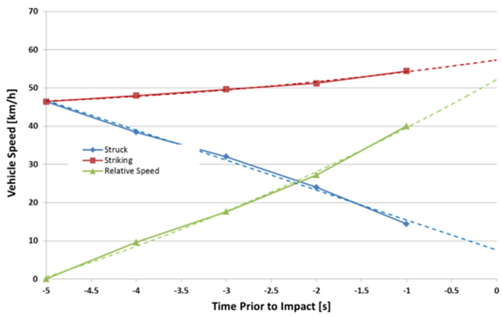

Figure 4: Time-Speed History of Vehicles Involved in a Rear End Collision.

In all the data plotted above, there is a gap between the last data point (typically T= -1.0 in the older EDRs) and T=0, the assumed crash time. As noted in Table 1, the timing of the sample points relative to the actual crash T=0 may be shifted by 1s. The dotted lines in Figure 4 show the predicted speeds of the vehicles based on the preceding intervals but it cannot be rigorously stated that the relative collision speed was the one identified at T=0 (52 km/h) in the graph, but may have been anywhere from 40 to 52 km/h, depending on the time of contact between the vehicles. The sensitivity of sample rate and time shift are discussed in the following analysis.

Crossing Paths

The preceding case contained no pre-crash steering input. A further analysis of a case with vehicles that crossed paths was investigated. The vehicle that crossed the path of the approaching vehicle had EDR data detailing the steering input. The steering data was stored at a lower sample rate than specified in Part 563 as the vehicle model preceded the implementation of Part 563. The steering and vehicle speed data were recorded in 1 second intervals, 7 seconds prior to impact. The vehicle speed was converted to effective braking deceleration and used with the steering information to predict the vehicle motions prior to the impact. A 3 DOF simplified vehicle model was used in a parameter study.

As described previously, the time of impact is unclear in the EDR data and there is no direct timing information between the crash pulse T=0 and pre-crash T=0. The sample timing within each one second interval is therefore unknown relative to impact. As shown in Figure 5, the data points can be at the start, middle or end of the one second interval. For this case it was assumed that all state variables (speed, steering wheel angle, brake switch status, etc.) were polled and recorded within a few milliseconds and no other timing shift existed within the sampling interval. Five possible sampling variations, essentially addressing 250 ms intervals, were investigated. These simulations could be combined to show the possible error in vehicle position or speed.

Figure 5: Possible timing of data points

Figure 6 shows the uncertainty of the pre-crash positioning of the vehicle given a common point of impact where the uncertainty of the vehicle position 7 seconds before impact can be seen at the left end of the curves. A similar diagram can be used with a given start point (at T=-7s) and see how much the impact point varies due to the timing uncertainty in the EDR.

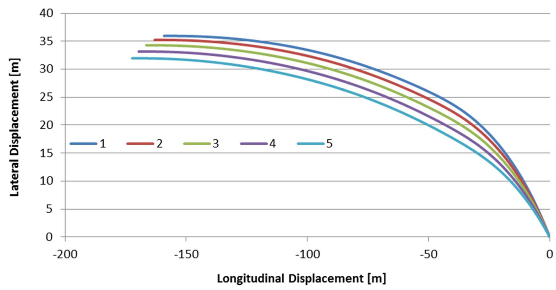

Figure 6: Uncertainty in pre-crash motion using common impact point as a reference

Vehicle dynamic models are sensitive to the road/tire parameters. An investigation of the sensitivity of vehicle trajectory to the tire model coefficients suggest that these parameters were not too influential on the results but exact comparison of the simulation results to the physical vehicle responses were not pursued in this analysis.

The pre-impact positioning of the vehicle (via simulation) using the EDR data was not able to accurately position the vehicle within the travel lane. As seen in Figure 5, the uncertainty of the vehicle position 7 seconds prior to the crash is on the order of a lane width (typically 3.5 m) and thus other information is needed to complement the EDR data if accurate positioning of the vehicle is needed.

The case had EDR data which contained rapid steering wheel motions in the last second before impact. This extreme handling condition can be simulated but the yaw rate of the vehicle needs to be available to determine if the vehicle model is correct and that the vehicle slip angles are consistent with the ESC system thresholds on the vehicle. The steering input caused a relatively high predicted yaw rate (40 deg/s) and could be near ESC system intervention. According to the EDR, no ESC intervention occurred. Without yaw rate data, it can be difficult to establish a reference condition for the vehicle dynamic simulations at the start of the simulation which also restricts the ability to accurately reconstruct the vehicle's position prior to impact.

The knowledge of the rest positions of the vehicle was needed to filter the possible solutions from the EDR. Given the uncertainty in the sampling times relative to the crash "0" time point, the range of impact speeds can create inconsistent collision speeds for the actual rest positions. Figure 6 shows that only Case 4 & Case 5 resulted in impact speeds consistent with the rest positions. This information could be used to refine the pre-impact position highlighted in Figure 5. When scene evidence was available, the vehicle positioning could be narrowed to within 1 m at the initiation of EDR recording (comparison of Cases 4&5 in Figure 5).

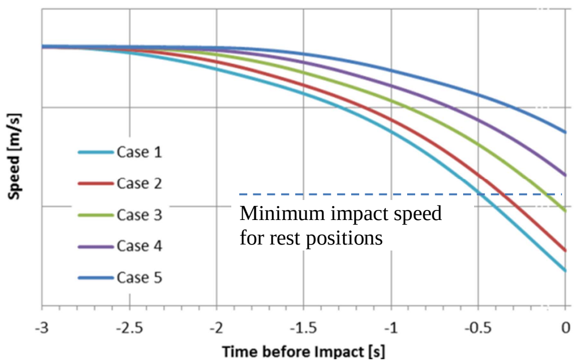

Figure 7: Vehicle speeds prior to impact

DISCUSSION

The historic application of EDR data has been the analysis of occupant injuries during a crash. The use of pre-crash EDR data elements has not been fully exploited to date. The development of active safety test procedures needs detailed data and EDRs provide important, objective data that cannot be not be reliably reported in analytical reconstructions.

EDRs are penetrating the vehicle fleet and the number of EDR files recovered in NASS can be expected to increase. For example there were over 1200 cases in 2011 compared to the 630 in 2009. Even without SRS deployments, EDR records of pre-crash data were available in the majority of cases. Collating the data over several years will increase the sample sizes for the different collision types and improve the analysis reliability.

The review of some of the individual cases highlights the need to validate the case information. Some data elements are subjective and reflect the investigators interpretation of the events. For example the rear end impact depicted in Figure 4 was identified as a vehicle striking a stopped vehicle when it appears the forward vehicle was actually decelerating. These details are critical for developing active safety tests as it creates different demands on the test devices. Test devices that represent a moving vehicle will require positioning requirements that must be repeatable and synchronised with the tested vehicle.

Two data elements were identified that need to be better defined if Part 563 to maximise the utility of EDR data. These parameters are the synchronisation of the time elements and the addition of yaw rate information. The pre-crash and crash events need to be synchronised so that speed, brake, and timing information can be more accurately interpreted. As seen in Figure 4, the difference in the pre-crash speed can differ considerably due to the timing uncertainty. Timing also is more important for synchronising the EDR records between two vehicles. Figure 4 does not address the timing uncertainty between the two vehicles and there can be a 2 second difference in the T=0 for each vehicle.

The sensitivity analysis identified in Figure 5 suggests that a 0.25 s sample interval (or 4 Hz sample rate) should be the longest sample period that can compensate for the T=0 time shift for pre-crash and crash records. Some modern vehicles are recording pre-crash data at 10 Hz and demonstrate that a 4 Hz limit is not an excessive burden.

The yaw rate information is a key omission in the Part 563 dataset. Steering wheel information is useful but the yaw rate allows any simulation/analysis of steering inputs to be validated by the actual vehicle response. Yaw rate information also allows the effectiveness of other countermeasures, such as stability control, to be assessed objectively. This information is part of a standard electronic stability control system and a crucial piece of information. The analysis of vehicle positioning also showed the combination of sampling uncertainty and missing yaw rate information could introduce errors in predicted vehicle orientation. The 1s uncertainty in impact time produced a 45 deg. positioning range.

The review of the NASS year 2009 cases was not sufficient to draw conclusions for active safety test development. The EDR data requires extensive pre-processing to make the data amenable to more automated analyses. The data does not dispute the suggested test conditions such as the NHTSA [4,5]or AEB Test Group [8] test protocols, but more analysis of the EDR data should help refine the procedures.

An important issue in active safety test development is the role of driver interventions during a safety critical event. Bagdadi [19] reviewed the naturalistic driving data and identified driving braking behaviour was different in safety critical events. Braking, throttle, or steering inputs during incidents that may activate a system need to be studied to ensure the system is robust. EDR data is an invaluable source for this analysis if the timing issues are better understood. Even with the timing uncertainty, brake application and braking effort can be extracted from EDR data with a 1 second precision. This is not possible with classic accident reconstruction techniques. The benefit of NASS cases is that the data is associated with safety critical events and is easier to extract (in large numbers) than in vehicles instrumented in naturalistic driving studies (NDS). The naturalistic driving programs can only run a limited number of vehicles and there may not be any events of interest recorded during the study period. A future fleet of 100% EDR equipped vehicles is essentially a fulltime, wide spread data acquisition system. If Part 563 is made mandatory in the proposed standard FMVSS 405 [20], then this future is not too far away.

LIMITATIONS

This exploratory study highlights the issues in using EDR data when designing standardised tests. Due to the limited information investigated in this study, no final recommendations for specific tests, but priorities for different research topics (pre-braking, steering inputs) are formulated from the data to date. Future work with a larger dataset is planned by the authors.

CONCLUSIONS

The study shows the importance of objective field data that is needed for designing new active safety tests. Although not explored in the paper, the data is also relevant for analysing the effectiveness of different systems when they become more prevalent in the fleet and data becomes available.

The pre-crash EDR is, to date, underutilised. This is partly due to the pre-processing needs, but an important issue is the uncertainty in the crash timing, relative to the EDR pre-crash data timing. As demonstrated in this paper, this error is not negligible and must be addressed in analyses, particularly the older data with one second sample rates.

EDR data, conforming to Part 563, provides the potential to improve for active safety test development in terms of:

1) Identifying pre-crash travel speeds of test vehicles
2) Identifying pre-crash speed profiles for test targets
3) Identify timing and magnitude of pre-crash braking relevant from real world events

Inclusion of better clock functions and yaw rate information in Part 563 will allow vehicle steering and vehicle positioning information to be incorporated into test protocols. Development of more complex scenarios can also be undertaken when more complete vehicle dynamics data is available.

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EVALUATION OF OCCUPANT PROTECTION DURING THE CRASH PHASE CONSIDERING PRE-CRASH SAFETY SYSTEMS – RESULTS FROM THE EC-FUNDED PROJECT ASSESS

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ABSTRACT

Research Question/Objective

Since integrated safety systems combine active and passive safety elements in one safety system, it is necessary to define new procedures to evaluate vehicle safety from the overall system point of view. The main goal of the ASSESS project is to develop harmonized and standardized assessment procedures for collision mitigation and avoidance systems.

Methods and Data Sources

In ASSESS, procedures are developed for: driver behaviour evaluation, pre-crash system performance evaluation, crash performance evaluation, socio-economic assessment.

This paper will concentrate on the activities related to the crash evaluation. The objective is to perform simulations, sled tests and crash tests in order to understand the influence of the activation of the pre-crash systems on the occupants' injuries during the crash phase. When a traffic accident is unavoidable, pre-crash systems work on various safety devices in order to improve the vehicle occupants' protection. Braking assistance and adaptive restraint systems are the main pre-crash systems whose effect on the occupants' protection will be described in this paper.

Results

The results will be a description of the effect of the activation of the pre-crash systems on the crash phase. Additionally, a set of recommendations for future methodology developments will be delivered.
Furthermore, a first approach to the study of the effect of the pre-crash systems activation on the occupants' protection when the impact is unavoidable will be presented. This effect will be quantified using the biomechanical values obtained from the simulation and testing activities and their related injury risks. Simulation and testing activities will consider the following scenarios:

- No activation of any pre-crash system
- Activation of one or a combination of several pre-crash systems

In this way, differences in the results obtained from different scenarios will show the effect of each pre-crash system separately during the crash phase.

Discussion and Limitations

The set of activities developed in this research project is limited by the fact that with the given resources only a limited number of vehicle models could be investigated. In addition, there are also limitations related to the injury risk curves and the passive safety tools currently on the market.

Conclusion and Relevance to session submitted

The paper will present a complete analysis of the effect of pre-crash systems during the crash phase when the impact is unavoidable. Details, limitations and first application experience based on a few examples will be discussed.

Currently, there is not any regulation, assessment program, or other similar official procedure able to assess pre-crash systems during the crash phase. This project comprises phases of traffic accidents which have been historically analysed separately, and aims to evaluate them taking into account their interrelationship. ASSESS is one of the first European projects which deals in depth with the concept of integrated safety, defining methodologies to analyse vehicle safety from a global point of view.

INTRODUCTION

Background

The overall purpose of the ASSESS project is to develop a relevant and standardized set of test and assessment methods and associated tools for integrated vehicle safety systems with the focus on currently on-the-market pre-crash sensing systems. In order to achieve this objective, methodologies and procedures have been developed for driver behaviour evaluation (WP3) and pre-crash system performance evaluation (WP4). WP5 was in charge of defining a methodology in order to assess pre-crash safety systems activation during the crash phase.

Injury risk curves were going to be the base of the methodology to evaluate the pre-crash systems activation during the crash phase. The idea was to draw injury risk curves relating the impact speed to the probability of injuries for the vehicle occupants. Specifically, it was planned to use two injury risk curves per biomechanical value: one considering the activation of improved restraint systems and the other one without considering it. The performance of simulation activities, sled tests and crash tests was going to be used in order to draw those curves. Figure 1 shows an example of the curves to be used in WP5.

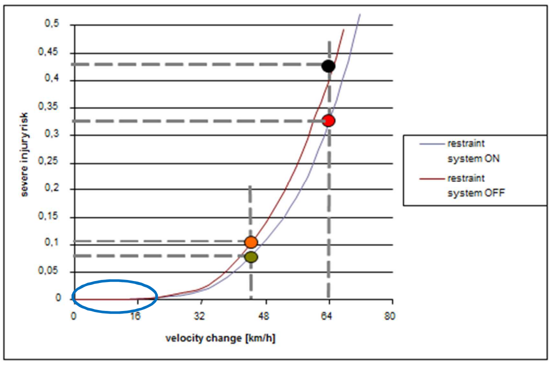


Figure 1. Generic injury risk curve (no real data)

The black point represents the reference test. If the impact occurs at the same speed but with the activation of improved restraint systems, the new injury risk is represented by the red point. On the other hand, if improved restraint systems are not activated but there is an impact speed reduction due to a pre-brake action, the orange point represents the new injury risk value. Finally, if both improved restraint systems and pre-brake action are activated, it is the green point which represents the injury risk level.

After performing the first simulation activities, it was detected that almost all biomechanical values had a related injury risk below 1% (AIS≥3, according to Mertz and Eppinger sources). This meant that all the coloured points explained in the paragraph above would be in the blue circle represented in Figure 1. Only chest deflection had a related injury risk over 1%.

In view of this, the objective of the WP5 of the ASSESS project as well as the activities to be performed were redefined. The new objective of WP5 was to perform a set of simulations, sled tests and crash tests in order to better understand the effect of the pre-crash systems activation during the crash phase. In addition, limitations of the currently on-the-market passive safety tools to satisfy this objective were going to be highlighted.

Activities performed

Below is a list of the activities performed in the WP5 of the ASSESS project in order to achieve the aforementioned objective.

- Braking manoeuvres
- Simulation activities by using MADYMO
- Simulation activities by using LS-DYNA
- Sled tests
- Full Frontal Impact test
- Offset Deformable Barrier Impact Tests

All these activities were performed to analyse the effect during the crash phase of the activation of the two main pre-crash safety systems currently on the market, which are:

- Improved restraint systems (pre-pretensioner)
- Pre-brake action

The activities listed above, which were performed considering the activation or not of the two main pre-crash safety systems, are described in the following section.

ACTIVITIES PERFORMED

Braking manoeuvres

The pre-brake action of a vehicle when an imminent accident is detected reduces the impact speed decreasing, consequently, the amount of energy transmitted to the vehicle occupants. This is obviously positive, but the pre-brake action has also a negative effect on the occupants of the vehicle: the deceleration pulse generated by the braking action provokes a forward movement of the vehicle occupants. This out-of-position complicates the work of the restraint systems of the vehicle since they are designed for a standard driving position.

In order to better understand this effect, several braking manoeuvres were performed with a Daimler S-Class. Three volunteers similar to a HIII 50%ile dummy were seated in position 3 of the car, and the displacement of their head, neck and shoulder during the braking action was measured by using tracking tools. The repeatability of the braking action was guaranteed by a braking robot, which performed two kinds of manoeuvres: full brake with pre-safe system activation and full brake without activating it. Figure 2 shows the range of displacements (in mm) obtained per body part, considering all volunteers, and separating them depending on the activation or not of the pre-safe system.

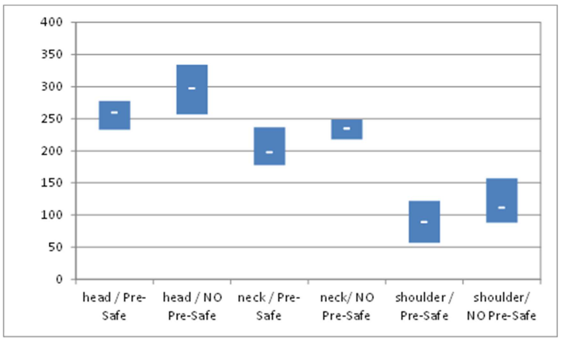


Figure 2. Generic injury risk curve (no real data).

In addition to quantifying the displacement of each body part, Figure 2 shows that the forward motion of the vehicle occupants is reduced when the pre-safe system is activated. In this case, the pre-safe system included a pre-pretensioner and anti-submarining mechanisms.

Simulation activities by using MADYMO

A complete set of simulation activities was performed by using MADYMO. These activities can be separated into two main groups:

Pre-crash phase These simulations were focused on the braking phase (before the impact). Multibody human body models (HBM) were used to analyse the forward motion of the vehicle occupants due to the braking action. Simulations were performed with a Citröen C3 model and using the two pulses shown in Figure 3.

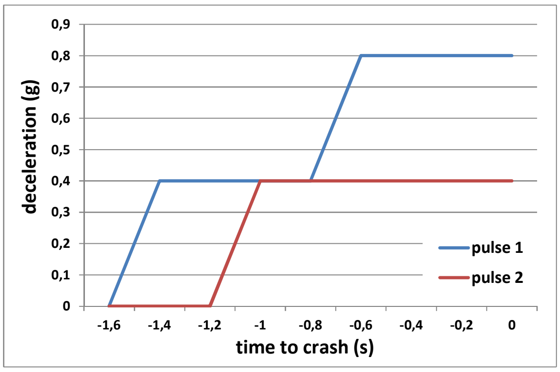


Figure 3. Deceleration pulses used to perform the braking phase simulations.

The abovementioned simulations were conducted considering not only the two pulse represented in Figure 3, but also the activation or not of the Active Control Retractor (ACR). Find in Table 1 the displacements resulting from these pre-crash phase simulations.

Table 1
Occupants' displacement

DRIVER	Pulse1		Pulse2	
Displ. in mm	ACR	No ACR	ACR	No ACR
Head	-192	-192	-37	-101
Thorax	-123	-137	-14	-108
Pelvis	+19	-60	+49	-18

PASSENGER	Pulse1		Pulse2	
Displ. in mm	ACR	No ACR	ACR	No ACR
Head	-179	-236	-44.8	-178.1
Thorax	-121.3	-173.3	-26	-138.1
Pelvis	-8	-53.5	-0.9	-24.57

Similarly to the braking manoeuvres, also in this case a reduction of the forward displacement of the vehicle occupants is detected when the improved restraint systems (in this case, ACR) are activated.

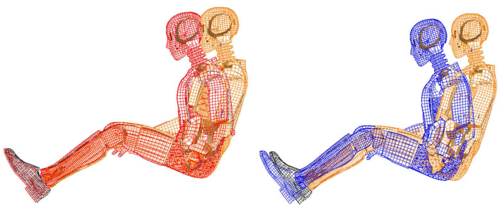


Figure 4. After braking position of the Hybrid III dummy in LS-Dyna simulations "with ACR" (left) and "without ACR" (right) activation.

However, to analyse in detail the results above it is necessary to take into account that these simulations were conditioned by some limitations, namely:

- Seat models only correlated for crash (not for pre-crash scenarios).
- Unknown level of the seat belt correlation.
- Correlation level of the HBM partially known.

Crash phase This group comprises those simulations which focused on the analysis of the injuries suffered by the vehicle occupants during the impact. According to the WP objective, these activities were performed considering the activation or not of the pre-pretensioner and pre-brake action.

Also in this set of activities a Citröen C3 model was used, but in this case it was virtually crashed against a deformable barrier according to the Euro NCAP frontal impact configuration. The occupant model used was the HIII Multibody model (muscles not strained). Impacts at 65, 56 and 40 km/h were simulated in order to reproduce the speed reduction generated by the pre-brake action. Additionally, all those impacts at different speeds were simulated with and without ACR activation and considering or not the "after braking" occupant' position obtained in the pre-crash simulations. In this way, the effect of the pre-pretensioner and the pre-brake action were going to be evaluated separately. Table 2 summarizes the configuration of the simulation activities comprised in the crash phase.

Table 2
Crash phase simulation activities plan

Impact speed	After braking positioning	Pre-pretensioner
64 km/h	no	no
56 km/h	no	no
40 km/h	no	no
64 km/h	yes	no
56 km/h	yes	no
40 km/h	yes	no
64 km/h	yes	yes
56 km/h	yes	yes
40 km/h	yes	yes

In line with the initial objective of the WP5 of the ASSESS project, the biomechanical values resulting from these simulation activities were related to their injury risks AIS≥3, according to Mertz and Eppinger sources. At this point, it was observed that all biomechanical values except chest deflection had a related injury risk below 1%.

The blue circle in Figure 5 shows the zone of the graph were almost all biomechanical values are situated.

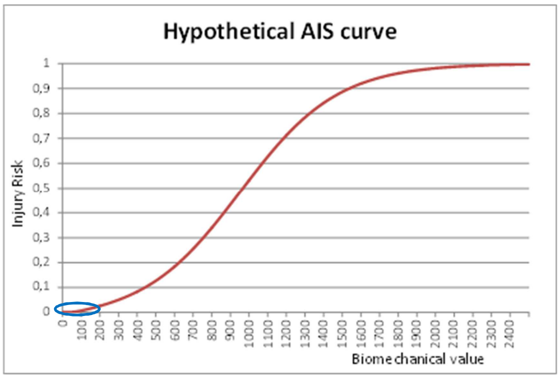


Figure 5. Hypothetical injury risk curve.

As explained in the introduction, in view of these results it was decided to change the WP5 objective in benefit of the better understanding of the effect of the pre-crash systems activation during the crash phase, without considering the definition a methodology based on the injury risk curves.

Simulation activities by using LS-DYNA

The simulations conducted by using LS-DYNA were focused only on the crash phase. In this case a vehicle buck model of a Mercedes E-Class was used, and the occupants were represented by Hybrid III 50% finite-element models . These activities were conducted focusing only on the passenger side (position 3) and considering the activation or not of the pre-brake action and pre-pretensioner. Similarly to the MADYMO simulations, the pre-brake effect was represented by crash tests at different impact speeds, all of them in a full frontal impact against rigid barrier configuration. The "after braking" position was taken from the HBM MADYMO pre-crash phase simulations explained in the previous section, by applying the displacements shown in Table 1 on the nominal position, (see Figure 4).

Four different configurations were simulated. First of all, the basic configuration, which is a full frontal impact at 56 km/h with the occupant in the standard position. Secondly, another full frontal impact with the dummy model in the standard position, but this time at 40 km/h. Then, a full frontal impact at 40 km/h considering the after braking occupant position without pre-pretensioner activation. Finally, the same impact at 40 km/h but considering the after braking occupant position with pre-pretensioner activation.

Figure 6 compares the biomechanical results obtained from the different variants of the simulations conducted.

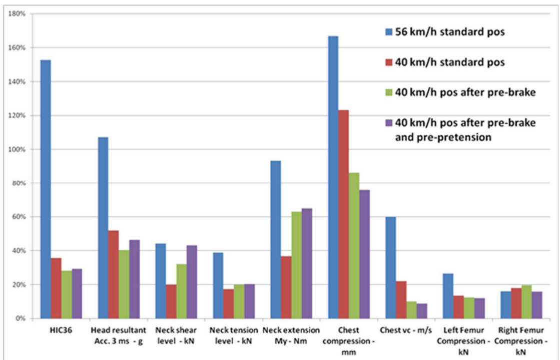


Figure 6. Biomechanical values resulting from each of the impact variants simulated.

From these results it is possible to affirm that the impact speed reduction due to the pre-brake action diminishes substantially most of the biomechanical values, mainly the ones related with the head and chest. On the other hand, the out-of-position generated by the pre-brake action worsens the biomechanical values related to the neck. The combination of pre-brake with pre-pretensioner changes the neck loads marginally.

Sled tests

Six sled tests were conducted using a Mercedes E-Class buck. Also in this case a full frontal impact against rigid barrier configuration was considered, making it possible to compare these results with the ones obtained from the LS-DYNA simulations. Similarly to the LS-DYNA simulation activities, also in this case the tests focused on the co-driver side. Only Speed reduction due to the braking action was studied also for the driver side.

In line with the activities described above and with the objective of the WP5 of the ASSESS project, sled tests plan was defined in order to analyse the effect of the pre-brake action and pre-pretensioner activation separately. Table 3 below shows the sled tests plan.

Table 3
Sled testing plan

V	Intention	Km/h	Driver	Pass.
1	Reference	50	50%	50%
2	Influence pre brake	50	--	50%
3	Pre- pretensioner (ACR)	50	--	50%
4	Reference	40	50%	50%
5	Influence pre brake	40	--	50%
6	Pre- pretensioner (ACR)	40	--	50%

According to the experience from several pre-braking tests in real cars with humans and dummies, the forward motion of the HIII dummy does not reliably represent the forward movement of a human during a braking manoeuvre. According to the paper 11-207-O presented by Daimler in the ESV Conference in 2011, this unreliability can be partially solved by introducing a piece of foam between the dummy chest and the seat belt. Since the pre-braking phase can physically not be reproduced on the sled, this foam has been not installed to perform these sled tests. However, in order to represent the influence of the pre-brake action, the initial position of the dummy has been taken from the abovementioned paper.

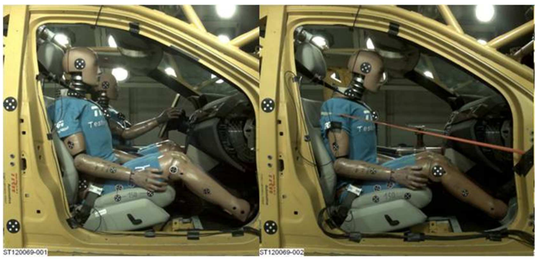


Figure 7. Initial position of the dummy in the sled tests considering or not the forward movement due to the braking action.

In real scenarios pre-pretensioners are activated approximately at the same time as the pre-braking actions, so the dummy forward movement has not started yet. In order to represent this situation in the sled tests performed, the dummy was positioned in its nominal position and, ~2.5s before staring the test, the pre-pretensioner was triggered. This pre-pretensioning supposed a maximum belt force of ~190N.

Figure 8 and Figure 9 below show the results for both driver and co-driver occupant positions according to the test plan shown in Table 3 and the abovementioned considerations.

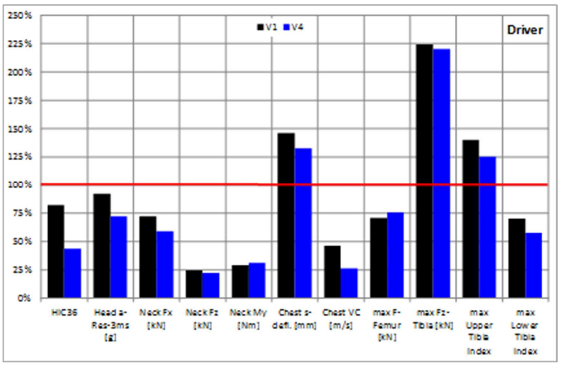


Figure 8. Dummy values for driver side compared to the Euro NCAP higher performance limits, V1 (50km/h, black) vs. V4 (40km/h, blue)

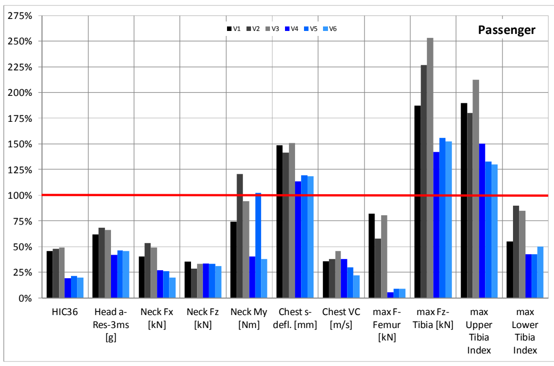


Figure 9. Dummy values for passenger side compared to the Euro NCAP higher performance limits, V1-V3 (50 km/h grey) vs. V4-V6 (40 km/h blue)

Similarly to the conclusions obtained from the LS-DYNA simulations, also in this case a clear benefit is observed due to the impact speed reduction for all the biomechanical values. Again, the forward motion of the dummy due to the braking action has a negative effect on the neck injuries (mainly in the My, in this case). In this case, an undesired early interaction between the dummy head and the deploying airbag was observed, which could explain this negative effect of the pre-brake action on the neck injuries. When the pre-pretensioner activation is considered, this occupant forward motion is reduced, minimizing the abovementioned undesired interaction and diminishing, consequently, the negative effect on the neck injuries.

Full frontal impact test

After performing several simulations and sled tests considering a full frontal impact test configuration, a full scale impact test was performed in similar conditions.

A full frontal impact test was performed with a Mercedes E-Class taking into account the effect of its own pre-safe safety systems. Daimler provided the information of a standard Full Frontal impact test at 50km/h. By performing another full frontal impact test, but activating the pre-safe systems of the vehicle, the benefit coming from these systems should be analyzed. In this way, the vehicle was accelerated by a hard brake action in order to impact at a speed close to 40km/h. Due to the braking action improved restraint systems were automatically activated . Figure 10 represents the configuration of the test performed.

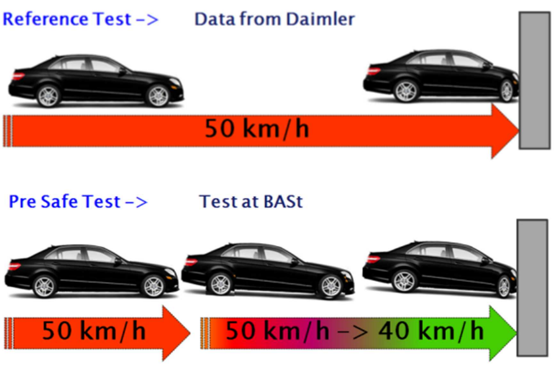


Figure 10. Schema of the full frontal test performed

The braking action was activated by using a robot which was attached to the braking pedal. This method guarantees the use of the braking system of the vehicle and, therefore, the achievement of a realistic deceleration pulse. Since the aim of this test was not the detection of an imminent impact, the improved restraint systems of the vehicle were activated by using an external trigger, which was situated at a specific distance from the impact point.

In order to make the forward movement of the dummies more comparable to a human during the braking phase, a piece of foam was situated between the seatbelt and the dummy chest according to the paper 11-207-O presented by Daimler in the ESV Conference in 2011.

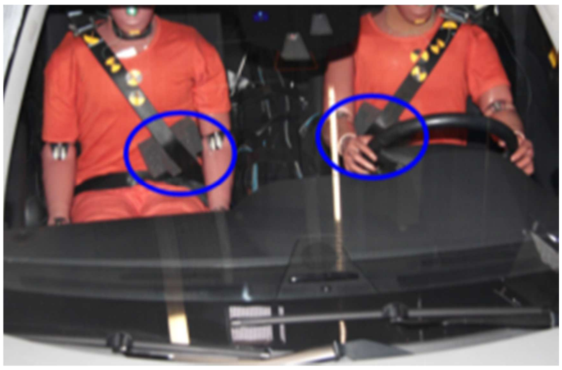


Figure 11. Picture of the foam installed between the seatbelt and the dummy chest.

After performing the full scale test at 40 km/h, the deformation of the structures during the impact were compared. Figure 12 shows that the impact speed reduction clearly diminishes the deformation of the frontal structure of the vehicle during the impact.

Figure 12. Comparison between the deformation of the structure in the reference test (left) and the test at reduced impact speed (right).

Comparing now the greatest penetration of the dummy head in the airbag (around 100ms after t0), a greater safety margin in the reduced speed scenario can be clearly observed, since the dummy remains further away from the steering wheel (see Figure 13).

Figure 13. Comparison of the penetration of the dummy head in the airbag at 100ms.

The abovementioned safety margin opens the door to an optimization of the restraint systems of the vehicle, for example, allowing a greater forward displacement of the dummy which could reduce the chest biomechanical values.

Regarding the biomechanical values, a clear benefit is observed when comparing both tests. The impact speed reduction due to the pre-brake action together with the activation of the improved restraint systems has a substantial positive effect on both driver and co-driver occupants. All biomechanical values of the co-driver dummy are reduced (see Figure 15). On the driver side, only the neck moment in Y direction (My) is not reduced.

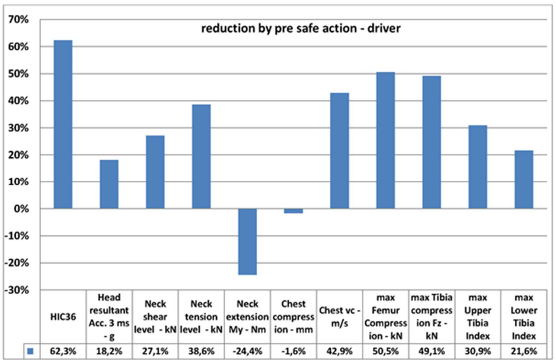


Figure 14. Reduction of the biomechanical values when pre-safe systems are activated. Driver side.

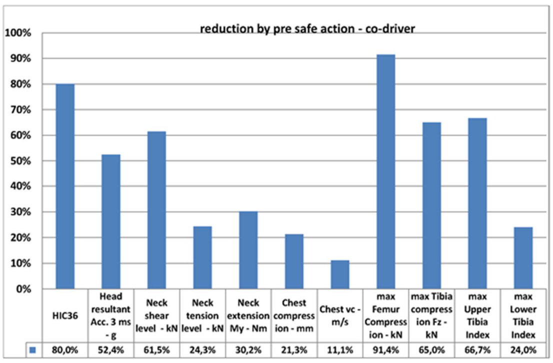


Figure 15. Reduction of the biomechanical values when pre-safe systems are activated. Co-driver side.

ODB impact tests

Two frontal impact tests with a configuration similar to the one defined in the Euro NCAP protocol were performed with a Citröen C3. Considering the official Euro NCAP test as a reference, two additional impacts were performed: one considering only the pre-brake action and another one considering the pre-brake action and the pre-pretensioner activation. In this way, the benefit of the pre-brake action and the pre-pretensioner activation could be evaluated separately.

In the two tests performed the vehicle was accelerated up to 64 km/h and, then, the braking system was activated to generate a deceleration pulse in order to impact at a speed close to 50 km/h.

Figure 16. Reduction of the biomechanical values when pre-safe systems are activated. Co-driver side.

Since the Citröen C3 does no incorporate pre-pretensioners, seatbelts incorporating this function were specially built to perform these tests. These seatbelts were set to the vehicle and controlled by a control box which was activated by an external trigger. In this way, it was possible to activate the pre-pretensioners at the right time.

In this case the braking action was generated by an external braking system able to introduce the suitable oil pressure into the ABS (anti-lock braking system) controller in order to activate the brakes of the vehicle in a natural way.

In a standard crash test, the vehicle is pulled by the propulsion system until 1 meter (approx.) before the impact. This pulling action not only accelerates the vehicle up to a specific speed, but also guides the car in the right direction, minimizing the risk of suffering impact deviations. In this case, since the vehicle need to brake before the impact, the propulsion system cannot guide the vehicle that much. It means that the vehicle will be freely moving during several meters, which increases the risk of impact deviations. In order to guarantee an offset within the limits specified in the Euro NCAP protocol, a specific guidance system was designed (see Figure 17). The aim of this system was to guide the car during the braking phase as close as possible to the impact barrier, but without jeopardize the free dynamic of the vehicle after the first contact time.

Figure 17. Photo of the test car, the test barrier and the guidance rollers.

Similarly to the full frontal crash, also in this case one piece of foam was situated between each seatbelt and each dummy chest according to the paper 11-207-O presented by Daimler in the ESV Conference in 2011.

Before start analyzing the tests results, it is interesting to mention that one of the main lessons learned in this part of the ASSESS project is the necessity of a better understanding of the dummy forward movement during the braking phase. Besides the two crash tests with pre-brake action, additional braking tests (without impact) were performed, and noticeable differences on the dummies forward motion were detected. Remarkable differences were also found when comparing the braking pulses, which are probably related with the differences between dummies' forward movement.

Figure 18 compares the deceleration pulses of the two crash tests with pre-brake action performed. Although their final value is similar (around 0.8g) there is a noticeable difference between the deceleration gradients to reach this 0.8g. This is a point to be better analyzed in future studies.

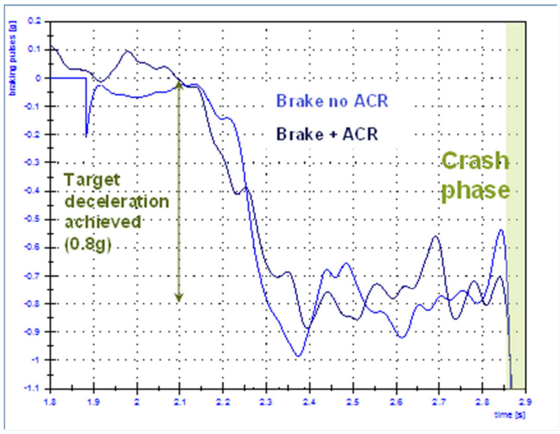


Figure 18. Comparison of the braking pulse of the two crash tests with pre-brake activation.

Regarding the dummies forward motion during the braking phase, it is possible to affirm that the slight forward movement observed during the pre-brake action when the pre-pretensioner is not activated disappears when the pre-pretensioner is activated.

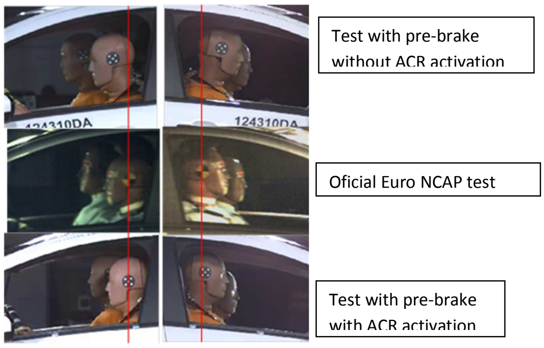


Figure 19. Dummy forward movement during the braking phase.

Starting now with the crash phase analysis, the first issue to be highlighted is the reduction of the deceleration pulse during the impact (see Figure 20). This pulse reduction is obviously beneficial not only for the structure integrity, but also for the occupants' injuries mitigation.

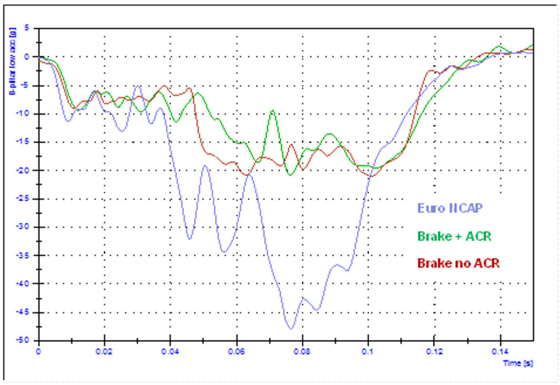


Figure 20. Crash pulses of the three ODB impact tests (reference test in blue, tests with pre-brake action in green and red).

Similarly to the full frontal crash test, the reduction of the impact speed had a direct effect on the structure deformation during the impact. Figure 21 shows a comparison between the maximum deformation of the structure in the reference test and one of the tests performed with pre-brake action.

Figure 21. Comparison between the deformation of the structure in the reference test (left) and one of the tests at reduced impact speed (right).

Focusing on the interaction between the dummies' heads and the airbag deployments, also in this case an important safety margin is observed for the tests with a reduced impact speed. The impact energy reduction diminishes the amount of energy required to restraint the dummies, so the vehicle's restraint systems can be optimized.

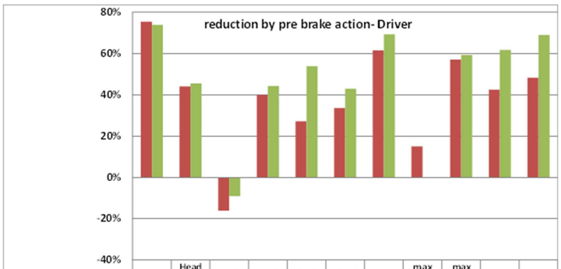
Figure 22. Head penetration into the airbag, driver side. Reference test on the left, test at reduced speed on the right.

An interesting effect was detected on the co-driver side when observing the interaction between the dummy head and the airbag. Comparing the two tests at reduced speed (with and without pre-pretensioner activation), a better dummy positioning (pre-pretensioner activation) together with the impact energy reduction due to the braking action worsens the interaction between the dummy head and the airbag (see Figure 23). This is a clear example of the necessity of adapting the vehicle restraint systems to the new energy level.

Figure 23. Head penetration into the airbag, Passenger side. Test with pre-pretensioner on the top, test without pre-pretensioner on the bottom.

Regarding the biomechanical values, the results and their related conclusions are similar to the ones obtained in the activities described above. The benefit on the occupants' injuries due to the impact speed reduction is clearly observed in both driver and co-driver sides. However, the forward motion of the dummies generates an increment on the neck injuries (neck shear level, in this case). The pre-pretensioner activation mitigates this effect on the driver side. In contrast, the neck injuries on the passenger side are higher when the pre-pretensioner is activated. This last counterintuitive effect is explained by the phenomenon shown in Figure 23.

With respect to the other biomechanical values and comparing only the two tests at reduced speed, almost all of them are reduced on the driver side when the pre-pretensioner is activated. On the co-driver side this positive effect is also appreciated, but to a lesser extent.



	HIC36	Head resultant Acc. 3 ms - g	Neck shear level - kN	Neck tension level - kN	Neck extension My - Nm	Chest compression - mm	Chest vc - m/s	max Femur Compression - kN	max Tibia compression Fz - kN	max Upper Tibia Index	max Lower Tibia Index
w/o ACR with pre-brake	75,4%	44,0%	-16,3%	40,0%	27,2%	33,6%	61,5%	15,0%	57,0%	42,6%	48,3%
with ACR and pre-brake	73,9%	45,6%	-9,3%	44,3%	53,8%	43,0%	69,2%	0,0%	59,3%	61,7%	69,0%

Figure 24. Biomechanical values reduction due to the braking action with (green) and without (red) pre-pretensioner activation on the passenger side.

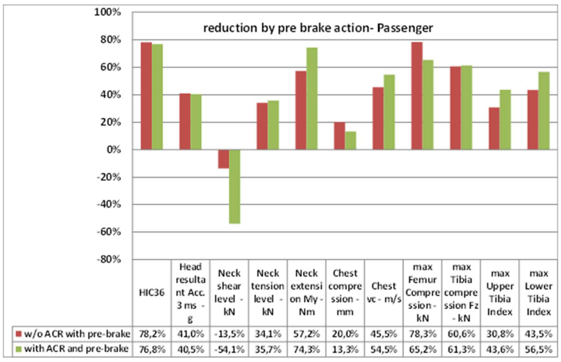


Figure 25. Biomechanical values reduction due to the braking action with (green) and without (red) pre-pretensioner activation on the passenger side.

INJURY RISK CURVES

At the beginning of this article it was explained that the initial objective of the WP5 of the ASSESS project was to define a methodology based on the injury risk curves in order to evaluate the effect of the pre-crash systems activation during the crash phase. In addition, it has also been explained that this objective was changed after obtaining the first simulation results, since they showed that all biomechanical values (except of chest deflection) had a related injury risk under 1% AIS≥3, according to Mertz and Eppinger sources.

After performing additional simulations, several sled tests and three different full-scale tests, it can be affirmed that the initial suspicions were correct. Hence, the use of the injury risk curves AIS≥3 to evaluate the effect of the pre-crash safety systems on the occupants' injuries during the crash phase when the impact is not avoided is ruled out. The only exception is chest deflection, which has a related injury risk high enough to be evaluated by using the injury risk curves (see Figure 26 below).

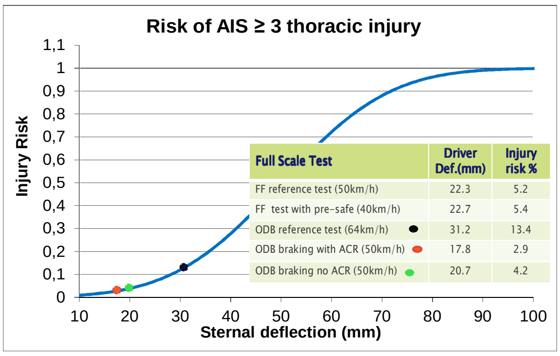


Figure 26. Risk of AIS≥3 thoracic injury.

At this point, two levels of injury risk can be distinguished: on the one hand the AIS≥3 curves, which are available, but only useful for the chest deflection evaluation; on the other hand the AIS<3 curves, which are not available so it is not known if they could be useful to evaluate the biomechanical values.

CONCLUSIONS

In this article several activities have been presented in order to better understand the effect of the activation of pre-crash safety systems on the occupants' injuries during the crash phase. Fortunately, similar conclusions can be drawn from the different activities.

First of all, it is important to highlight the notable benefit obtained from the activation of pre-brake systems,, which has been observed in all the activities conducted. The consequent impact speed reduction diminishes the kinematic energy at the impact time, reducing substantially the energy transmitted to the vehicle occupants and reducing, consequently, the injuries suffered by them. In addition, this energy reduction allows an optimization of the restraint systems in order to minimize even more the injuries on the vehicle occupants'. The impact speed reduction is also beneficial for the structure integrity, since vehicle deformations during the impact have also been diminished.

The effect of the pre-pretensioner also seems to have a positive effect in reducing the occupants' injuries, but to a lesser extent than the pre-brake action. Some differences can be found when comparing the effect of the pre-pretensioner activation on the occupants' injuries during the crash phase depending on the passive safety tool used to analyse it. Probably the sensitivity of the currently on-the-market passive safety tools is not high enough to reliably quantify this benefit.

The new objective of the WP5 of the ASSESS project was not only to better understand the effect of the pre-crash safety systems during the crash phase, but also to detect the limitations to perform a methodology in order to evaluate it. In this field, it is important to highlight the necessity of better understanding the relation between the forward motion of the dummies during the braking phase and the forward movement of a real human under the same circumstances. It is also remarkable that, since biomechanical values have no sense by themselves, more sensitive AIS curves are required in order to relate those biomechanical values with a real human injury. Finally, it is necessary to enhance the reproduction of a repeatable braking pulse in the laboratory.

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AUTOMATIC EMERGENCY BRAKING FOR PEDESTRIANS EFFECTIVE TARGET POPULATION AND EXPECTED SAFETY BENEFITS

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ABSTRACT

Automatic Emergency Brake (AEB) for pedestrians is a technology that automatically applies braking force to a vehicle when forward detection sensors determines that a collision with a pedestrian is imminent, thereby assisting in avoiding the collision altogether, or if it is unavoidable, reducing the impact speed of the crash and subsequently the risk of fatal/severe injury to pedestrians. The driver might be first notified about the danger by a tone or a visual warning or by an haptic feedback in the brake. If the driver does not act and if the impact is considered as inevitable, an automatic braking is applied. Notification step can also be skipped and the system brakes when the imminent collision is detected. Braking strategies vary across systems in terms of operating speeds range, adjusting the level of the braking force and the time when impact is considered inevitable. The value of deceleration is generally limited to 0.6 g.

The aim of this study is two-fold:
- Examine in which particular crash situations this kind of systems is relevant. In France, pedestrian crashes account for 15 % of injury crashes. However, there are a few considerations that might dramatically reduce this a priori aggregated target population: Performance of sensors varies across models and suppliers. A small range of different in-vehicle enhanced braking systems are currently available that involve differing activation processes and functionality, and likely to provide varying benefits in terms of fewer crashes and mitigations vehicle/pedestrian fatalities and serious injuries
- Propose an evaluation of the expected safety benefits of such systems

A detailed analysis of pedestrian crashes was carried out with the help of European in-depth crash data as well as police reports. Results show that, pedestrian crashes happen more often in cities, in the daytime, whereas the pedestrian crosses the street. Expected effectiveness of AEB pedestrian, if 100 % of the fleet is fitted with a perfect system that never fails, would be a reduction of 15.3% of fatal pedestrian crashes and 38.2% seriously injured pedestrian crashes each year. These would amount to 1.3% and 3.8% of all fatal and serious injury crashes respectively that occur annually in France.

INTRODUCTION

Automatic Emergency Brake Pedestrian (AEBP) is a technology that automatically applies braking force to a vehicle when forward detection sensors determines that a collision is imminent, thereby assisting in avoiding the collision altogether, or if it is unavoidable, to reduce the impact speed of the crash and subsequently the risk of fatal/severe injury to vulnerable road users. (Bond et al., 2003). Although there are several variations of these systems (some providing full and others, partial braking), they all aim to reduce the speed and stopping distance of a vehicle prior to impact in an emergency.

The amount of brake force applied is a continuous function involving factors such as relative speed, relative distance, collision probability and target classification. To this effect, some AEBP's only apply partial (i.e. semi-automatic) braking, with other systems applying maximum braking force (Bond et al., 2003). The objective of these systems is not only to provide continuous braking control throughout a potential collision situation, but also to provide the driver with increased time to react and regain control of the vehicle.

The term Automatic Emergency Braking Pedestrians (AEBP) is used to cover a wide diverse range of systems available by different technology manufacturers (Grover et al. 2008). Studies of the benefits of AEBP in reducing fatalities and serious injuries on the road are rare as the technology is still not widely available in passenger cars.

DEVICE DESCRIPTION

The particular system of interest here involved automatic braking in emergency situation when the sensors detect a pedestrian. It comprises radar located in the very front of the vehicle and a frontal camera accommodated in the central rear-view mirror. The camera and the radar work together with braking systems such as ESC (Electronic Stability Control) to help the vehicle stop quickly and either avoid the crash altogether or mitigate the injury to pedestrians.

The camera and the radar detect the target pedestrian and determine the collision speeds. The drivers might be notified about the danger by sound or visual warnings or by feedback in the brake. If the driver does not act and if the accident is considered as inevitable, braking is applied automatically to help to minimize the consequences of the accident.

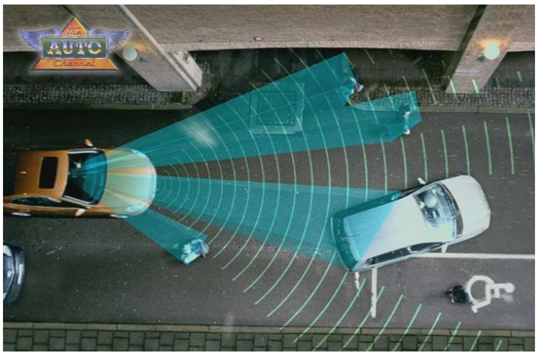

Figure 1. This is an example of the AEBP Pedestrian Technology of interest here.

Functionality

The literature shows that the AEBP declines differently according to the equipment manufacturers and the car manufacturers. So far, only Volvo cars propose AEB pedestrian on his models (S60, S80, V40, V60, V70, XC60, and XC70) as well as Lexus on the LS. Volvo claims that their system should help avoiding a collision with pedestrians at speeds up to 22 mph, and mitigate injuries at slightly higher speeds. The system is built on the safety city systems that helps preventing or mitigating rear-end crashes at low or moderate velocities. The driver is first alerted by a sound signal together with a flashing light in the windshield’s head-up display. In order to prompt an immediate, intuitive reaction, the visual warning is designed to look like a brake light coming on. If the driver does not respond to the warning and the system assesses that a collision is about to happen, the car’s brakes are applied with full braking force. The car only brakes if it is too late to steer away and applies the brakes less than a second before the calculated impact time. This feature uses a combination of a radar sensor and a camera to identify standing or moving pedestrians within a 60° field of view in daylight. A new dual mode radar detects objects of any shape and measure the distance to them. The camera determines what type of objects they are. To be able to classify an object as a pedestrian the sensing devices need to read an entire contour line of a human. The body has to be 31 inches or taller. Note that the detection can be disturbed if the human shape is distorted by certain clothes or if the person is carrying something (Volvo web site, www.volvocars.com).

Mobileye also provides a Smartphone application with a few driving aids, including Mobileye PCW (Pedestrian Collision Warning) that alerts to a possible collision with a pedestrian or bicyclist ahead. This application is only a warning and works only with a smart phone camera.

For the purpose of this analysis, we did not refer to the existing systems. It was assumed that the system slows down the vehicle automatically if an obstacle is detected and a collision is unavoidable, at any initial speed of the vehicle. Initially, deceleration is limited to 0,6g (approximately $6m/s^2$), depending on the difference of speed between the car and the pedestrian. When there is risk of collision with a pedestrian, a sound signal is emitted and a message appears on the multiple displays. Should the distance between the vehicle and pedestrian continue to decrease, the AEBS system automatically brakes the vehicle at 60% of the optimal deceleration (0.6g), and the system tugs the seat belt two or three times, to further alert the driver. The warning signal sounds again and a message appears on the multiple displays. The levels of final braking adopted here are shown in Table 1.

PEDESTRIAN ACCIDENTS

Pedestrians are with two-wheelers, the most vulnerable road users. The road rules define the pedestrian as a person who walk on the road. Are also considered as a pedestrian:

- People who drive a car child, or invalid people, or other small vehicle without engine;
- People who push/pull by hand bicycle or moped;
- Disabled people in wheelchairs driven by themselves or moving at walking pace.

At the world level

In March 2010, the General Assembly of the United Nations launched a Decade of Action for Road Safety 2011-2020. The objective is to stabilize and reduce the expected number of fatalities due to road accidents in the world. According to the OMS, road accidents cause 1.2 million fatalities annually (2.2% of all fatalities and not less than 50 million injuries. Approximately 46% of people who die on the roads in the world are pedestrians, cyclists and drivers or passengers of motorized two-wheelers, that is to say "vulnerable" road users. Pedestrians account for 22% of fatalities. China, India, Ethiopia, Russia, the Democratic Republic of Congo and Bangladesh alone accounts for 50% of pedestrian fatalities recorded in the world.

At the European level

In 2010, 6,051 pedestrians were killed in a road accident in the EU 27 countries. Pedestrians represent 19% of all fatalities. It is, in Europe, the main vulnerable road users and the second category of users most affected in terms of mortality in road accidents (after car passengers). They are therefore an important issue in the management of road safety for many European countries.

In 2010, nearly 1 pedestrian fatalities out of 3 are in Slovakia (39%), Lithuania (36%), Poland (32%) or Latvia (32%). In 2010, the European countries that account for the highest percentage of pedestrian fatalities are still Poland and Romania with 31% of pedestrian fatalities in Europe. We observe in these countries the greatest risk of being killed as a pedestrian in comparison to the number of inhabitants and the number of vehicles in traffic. Countries of Northern Europe and Central Europe have the lowest percentage of pedestrian fatalities compared to all road deaths (10% for the Netherlands, 12% in Belgium and France, 13% in Germany, Finland and Luxembourg). Thus, for the Eu-27 pedestrian fatalities rate is 1.2 per 100 000 inhabitants.

In France

For over thirty years, in France as in many other European countries, the number of pedestrians involved in an accident tends to decline, but the issue remains important: 485 fatalities, 4,584 injured and hospitalized injured people, 7,502 light injured people in 2010. Accidents involving pedestrians represent at least in 2010, 18% of traffic accidents. In details, in France, in 2010, pedestrians represented 12% of fatalities, 15% of hospitalized injuries and 14% of slight injuries. Among all pedestrians involved in an injury accident in France (n = 12 797), 4% are fatalities, 36% are hospitalized, 58% are slight injuries and 2% are uninjured.

The number of pedestrian fatalities against other users has declined since 2009 except against heavy vehicles, public transport and especially against motorcycles. The percentage of these fatalities increased to 20% against motorcycles while the fleet increased to 2.7%. The risk of being killed as a pedestrian per 100,000 motorcycles increased from 1.1 in 2009 to 1.7 in 2010. Whatever vehicle types against which he had an accident, the risk of being killed per 100 000 vehicles is about 1.

94% of pedestrian accidents in France take place inside urban areas. 71% of pedestrian fatalities, 93% of hospitalized and 97% of slight injuries are in urban areas. Approximately 74% of pedestrian accidents occur during the day and only 26% at night. However, according to the table below, we observe that more than half of those fatalities are at night. For all France, the risk of being killed as a pedestrian for 100 injuries is in urban areas 2.4 times higher at night than during the day and in rural areas 3.5 times higher. The risk of being severely injured is slightly higher at night than during the day, whatever the accident location (Table2).

Table 2.
Urban and rural pedestrian accident distribution in France

2010	Urban accident		Rural accident		Total
	Day	Night	Day	Night	
Accidents	71,4%	23,5%	2,5%	2,6%	100%
Fatalities	39,9%	31,6%	6,3%	22,2%	100%
Severe injuries	69,9%	23,5%	3,1%	3,5%	100%
Slight injuries	73,5%	23,5%	2,0%	1,0%	100%

The most frequent crash type is when the pedestrian crosses the street/road, from the right, and then from the left. In 30 % of injury crashes, the pedestrian is initially hidden, in other crashes, the pedestrian is lately detected or detected by the driver sufficiently soon but the driver does not expect the pedestrian to cross the street (Brenac et al., 2003).

METHODOLGY

The objective of this study therefore was to estimate the crash injury benefits of AEB Pedestrian, for pedestrians in France. These benefits were examined in regards to the number and proportion of fatalities and hospitalized that could be saved per annum. As noted earlier, AEB Pedestrians is considered to be useful for reducing pedestrian crashes, thus the analysis, therefore, was confined to this crash types. We assume also that AEBP is working in all road condition types (brightness, weather conditions,…).

The HARM reduction method was used to establish the potential road safety benefits for AEBP. The HARM approach has been widely used by MUARC in previous similar studies for quantifying road trauma reductions in terms of crashes saved and injuries mitigated. This method has been found to be particularly useful in assessing the benefits of new safety technologies. The most common method adopts a case-by-case analysis of a representative sample of crashes where the researcher selects crashes amenable to the technology and assessors what the crash outcome would have been had the vehicle(s) been fitted with the technology. The sum of these individual savings is then expressed as the benefit of the technology. This is outlined in more detail below.

Databases Used

Two datasets were used as part of the AEBP analysis. These included the French national accident database "Bulletin d'Analyse d'Accident Corporel (BAAC)" which supplies descriptive data per pedestrian and vehicle occupant crash. Data from 2005 to 2009 was provided for this analysis, containing a total of 761,960 cases at an average of 152,392 per annum. In addition, the European Accident Causation Survey in-depth database (EACS) from 1995 to 2001 was used for the case analysis comprising an average of 270 cases per year from Germany, Finland, Italy, the Netherlands, Spain and France. Together, these two databases were used to assess the likely reductions in crashes and injuries had AEBP technology been on-board.

The US National Automotive Sampling System, Crashworthiness Data System (NASS CDS) database was also used to construct injury risk curves, given its extensive case numbers across the investigated crash types. Data from 2000 to 2006 was used for this analysis, involving 73,153 vehicle occupants and pedestrians at an average of 10,450 collisions per annum. These in-depth data are a weighted representative sample of police-reported crashes that occur in the US each year, with detailed information regarding the crash, the vehicle involved and its occupants collected from a variety of sources.

Analysis Procedure

Using the Harm method presented briefly earlier, a detailed case-by-case analysis was used to calculate the crash and injury benefits of AEBP across the crash types of interest. First, relevant crash cases of pedestrian within the EACS database were identified, based on the type of crash reported by the crash investigators as specified by the EACS crash protocol. Given the focus on fatally and seriously injured pedestrians, cases with no injuries were excluded. All cases were entered into an Excel spreadsheet together with key variables including the accident, vehicle and occupant numbers, occupant age and sex, whether the vehicle braked or not, the braking distance, initial estimated speed and impact speed, road surface condition (wet, icy or dry) and the Injury Severity Score, calculated using the appropriate formula. For braking cases, whether or not ABS was present was also recorded. Braking and non-braking cases were treated separately. For cases where the brakes had been applied pre-crash, the relevant AEBP deceleration rate was applied, according to the road surface condition. Normal deceleration was assumed from when the brakes were applied, until 0.6 sec prior to the crash, after which the full AEBP deceleration rates were applied according to the specifications in Table 1.

Table 1.
Deceleration according to the surface adherence and braking system

Braking system	**Surface adherence** **Dry Road**	**Wet Road**	**Icy Road**
If ABS used	$-7 m/s^2$	$-5 m/s^2$	$-1 m/s^2$
If ABS not used	$-5 m/s^2$	$-3 m/s^2$	$-1 m/s^2$
With AEBP	$-10 m/s^2$	$-6.5 m/s^2$	$-2 m/s^2$

For non-braking cases, it was specified that AEBP would only operate for the final 0.6 sec before the collision. For the first 0.3 sec, half the maximum deceleration specified in Table 1 was applied (time to prepare the brake system), thereafter, full braking deceleration was allowed for the remaining 0.3 sec. For both braking and non-braking cases, a revised impact speed for each of these cases was computed assuming AEBP performance criteria, using the geometric calculations in Equation 1. In some cases, these figures showed that the crash could have been avoided completely (a negative impact speed was computed):

$$V_2 = \sqrt{V_1^2 + 2a * s} \qquad (1)$$

Where:

V2 = Revised impact speed (m/s)
V1 = Pre-crash travel speed (m/s)
a = acceleration (m/sec2), the maximum obtainable, given friction coefficient.
s = Braking distance (m)

For a positive revised impact speed, injury risk curves were then employed to estimate what the likely injury outcome would have been for the crash case. Figure 2 and 3 shows the probability risk curves used for pedestrian by impact severity.

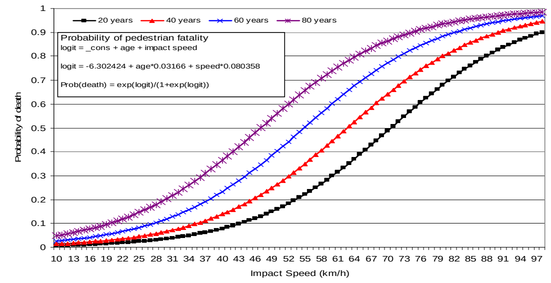

Figure 2. Age-adjusted pedestrian fatality risk curve, given impact speed (Source: Fitzharris & Fildes, 2007)

The revised probability of fatality curves showed the likely improvement in outcome that could be attributed to the technology. The equation derived from the best-fitting trend-line was applied to the fatal EACS cases to calculate a probability of death value for both pre- and post-AEBP (i.e. for pre-AEBP, the initial impact speed was included, with the AEBP impact speed used for establishing the post-AEBP probability of death). In order to derive the predicted percentage reduction in fatalities for AEBP, the values for each case were added for AEBP pre-AEBP and post-AEBP probability of death, with the following equation then applied:

$$X = 100-(P_2/P_1)*100 \qquad (2).$$

Where:

X = percent reduction in fatalities due to AEBP

$\mathbf{P_2}$ = Added total for probability of fatality for all dead occupants, post-AEBP

$\mathbf{P_1}$ = Added total for probability of fatality for all dead occupants, pre-AEBP

The revised injury severity outcome in terms of Injury Severity Score (ISS) was then estimated from a Figure 4 derived again from the NASS/CDS database and used to categorize the degree of injury for those cases that now survived.

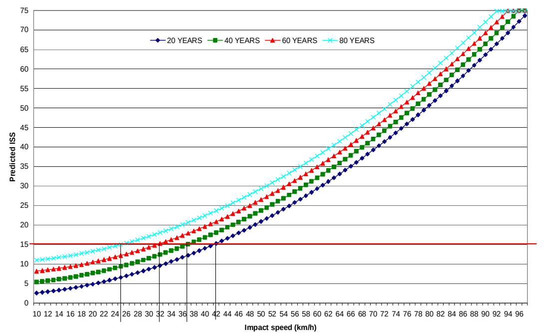

Figure 3. Predicted ISS on the basis of impact speed (Source: Fitzharris & Fildes, 2007)

These figures for each EACS case were then summed to estimate the proportional reduction in crashes, fatalities, serious and minor injury and no injury were then determined for AEBP from the EACS database, assuming 100% fitment to all French passenger vehicles. In computing the overall benefit if every passenger vehicle in France was fitted with AEBP, the proportional savings from the EACS crashes were applied to the French national crash statistics (BAAC), adjusted based on the relevant proportional differences of each crash type between EACS and BAAC.

CASE STUDY

To assist in understanding the procedure for estimating the benefits of this new technology, a single exemplar pedestrian case from the EACS database was employed and the various steps undertaken are illustrated below. Care needs to be taken in understanding these outcomes using this prospective approach given the assumptions necessary in making these computations.

The case chosen involved an 8 year old boy who was struck by a braking vehicle traveling initially at 110km/h that was braking on a dry road for 43 meters prior to the collision at a deceleration rate of just around $5m/s^2$ and struck the boy at 81kmh. He sustained fatal injuries from the crash with an Injury Severe Score (ISS) of 75 (max) and died at scene. The following outlines the procedure adopted to estimate what the outcome would possibly have been had the vehicle been fitted with an Automatic Emergency Braking System.

Using Equation 1, the pre-AEBP deceleration rate was calculated at $4.97m/s^2$ and the time to collision over the 43 meters from the moment of braking was 1.41 seconds. In calculating the new deceleration rate, it was assumed that over the first 0.81 seconds, the normal deceleration rate of $4.97m/s^2$ would have applied, and the vehicle's velocity would have reduced from 110km/h to 94km/h when the AEBP intervened. From then on, the vehicle would have braked more severely at $10m/s^2$ (it was noted to be a dry road) reaching a final velocity of 70km/h at the moment of impact. The crash would still have happened however, and the effect of the AEBP technology for this crash would have been a reduction in impact severity from 81km/h to 70km/h, a reduction of 11km/h or 86% of the original value.

Probability of Death

From Figure 2 using the appropriate curve (20 years was chosen from the 3 available), the probability of death for the initial impact speed of 81kmh was estimated to have been 0.70 (70% probability or for every 100 such crashes, 70 of them would have resulted in a death for this impact speed). This is a high value and consistent with the boy having been killed in the crash.

Now that the revised impact speed has been estimated to be only 70km/h with AEB technology, this equates to a probability of death of 0.5, that is, a 50% likelihood of being killed. It would be expected that at this probability level (a 1 in 2 chance), the child could possibly have not been killed in this crash, although he would still have been seriously injured.

Serious Injuries

There was a reasonable chance that the 8 year old subject here may have survived the crash with a reduced 70km/h impact speed, but would still have been seriously injured. To estimate what his injury severity level would have been, we refer to Figure 4 that was NHTSA cases. Using the formula for translating impact speed in a pedestrian crash to Injury Severity Score, we found a revised ISS value from 75 (max ISS for a death) to around 40 at the lower impact speed.

It is important to note that ISS is not a continuous scale as it is derived from adding the maximum AIS scores (squared) for up to 3 body regions. Hence, it is technically impossible to get certain numbers and fractions (it is a non-monotonic). More details on ISS and AIS are available on request.

An ISS value of 40 is still considered to be a serious life-threatening injury. Had the boy survived this crash, he would have still sustained very severe injuries. Trauma specialists report that injuries at these levels are associated with long stays in hospital and survival is determined by the type of injury, where it occurred and whether it can be properly treated as well as the patient’s ability to recover. Moreover, injuries of this level can be associated with a degree of ongoing permanent disability.

Computing AEBP Benefits

The prognosis for this particular case post-AEBP using the assumptions specified was good in terms of a potential life saved but with a severe injury outcome and the possibility of ongoing long term impairments. Had the case been one of initial survivable injury, it is likely that this would have translated to a lesser severity injury from the reduction in impact speed. We would then have interpreted this as a percentage of injury saved by AIS or a “shift” in injury severity that could be attributed to the technology.

From the in-depth EACS case analysis, we can determined what the number of fatalities saved by summing these across the total cases and determine the percentage reduction in deaths and then apply these percentages for the total fleet in the French National database (BAAC data) to estimate the annual fatality benefit. Thus, while the outcome for this fatality was positive (the child would have lived), nevertheless, the injuries sustained need to be subtracted from the total injury saved to arrive at the true benefit from the technology. In this calculation, we simply subtracted this percentage outcome (assumed it would have been classified as Severe in this analysis) to what we finally determined to be the total injury severity saved, to arrive at the overall total benefit.

RESULTS

The number of fatalities and seriously injured occupants in France from 2005 to 2009 is shown in Table 3.

Table 3.
Fatal and severely injured persons (BAAC Database)

French National Crash Statistics						
	2005	**2006**	**2007**	**2008**	**2009**	**Average**
Fatalities	5,318	4,709	4,620	4,275	4,273	4,639
Hospitalized	39,811	40,662	38,615	36,179	38,813	38,816

Pedestrian crashes

As shown in Table 4, 15.3% of pedestrian would be expected to be saved each year in France if every vehicle was fitted with AEBP.

Table 4.
Expected fatal and serious injured pedestrian crashes affected by AEBP

Outcome	**Savings**
Number of fatal Crashes Survived (n=379)	58
Percent fatal pedestrian crashes saved	15.3%
Percent fatal crashes saved in France	1.3%
Number serious injury crash saved (n=3959)	1,514
Percent serious injured pedestrian crashes saved	38.2%
Percent serious injured crashes saved in France	3.8%

Of the 379 fatal pedestrian crashes in pedestrian to passenger car crashes that occur in France each year (2005-2009 average), 58 (15.3%) were estimated would have been saved by the widespread fitment of AEBP technology. Based on an average of 4,639 road fatal crashes that occurred each year in France between 2005 and 2009, these estimated savings equate to 1.3% reduction overall in French road fatal crashes from AEBP. For 62% of these previous fatal cases, the computed level of injury would be downgraded to serious, 24% to

minor or no injury and 14% of the crashes would have been avoided altogether.
Of the 3,959 seriously injured pedestrian crashes annually in France, it was estimated that 1,514 crashes (38.2%) would have been influenced by AEBP equating to a 3.8% potential saving in the total number of 38,816, serious road injury cases in France each year. Of the 1,514 crashes affected, 88% would have been reduced to minor injury crashes, while the remaining 12% involved no injury or the crash was avoided.

Adjusted Benefits

It should be noted, however, that these savings are independent and do not include the additional increase in serious and minor injury cases from the downgrading of fatal cases to less serious injury outcomes. That is, the 58 pedestrian fatal crashes would no longer be fatal outcomes.
The expected fatal and serious injury crash reduction benefits for AEBP were then combined to reveal the final KSI outcome benefits for AEBP among pedestrian and rear-end crashes. According to the proportional benefits indicated above, the benefits and redistribution of these cases, due to the influence of AEBP, are shown in Tables 5.

Table 5.
Combined fatal and serious injury outcomes for pedestrian cases with AEBP

Injury Outcome	**Fatal Cases** (n=379)	**S. I. Outcome** (n=3959)	**S. I. Outcome** (adjusted)	**Adjusted Savings**
Fatalities	321	-	-	58 (1.3%)
Serious Injuries	36	2445	2481	1478 (34.1%)
Minor/non-injured or crash avoided	22	1514	1478	2802 (64.6%)

From these data, it was found that with an average of 4,338 KSI crashes (Killed and Seriously Injured) pedestrian injury cases per annum in France, the combined outcome showed a saving of 58 fatal and 1,478 serious injury crashes. While there would be some overflow increase in minor injury crashes from the downgrade of KSI cases, these would also be offset by savings in minor injuries, non-injured crashes and additional crashes avoided altogether from AEBP which were not calculated here.

DISCUSSION

The focus of this study was constrained to estimating only fatal and serious injury crash savings for AEBP technology described earlier in pedestrian crashes. These were considered to be the major crash types likely to be influenced by the technology where most of the benefits would accrue.

Pedestrian crashes

The results of this analysis show a potential important estimated reduction in fatal and serious injuries to pedestrians resulting from the fitment of AEBP technology to all vehicles in France. Fifty-eight (15.3%) of fatal pedestrian crashes each year and 1,514 (38.2%) seriously injured pedestrian crashes would be saved in France each year, based on the average number of these crashes that occurred during 2005 to 2009. These would amount to 1.3% and 3.8% of all fatal and serious injury crashes respectively that occur annually in France. These figures are of course very much dependant on the assumptions we made about a generic operation of such system.

While there would be a small increase in serious injury outcomes from the redistribution of fatal case outcomes, nevertheless, there would still be a sizeable reduction of 1478 serious injuries from the widespread use of this technology. There would also be additional reductions expected in minor injury and non-injury crashes as well as crashes avoided, although these computations were not the focus of this study. Furthermore, these benefits would be cumulative benefits each year.

Several earlier studies on the benefits of Brake Assist alone BAS (activated by emergency pedal action) have been carried out. One predictive study by Page et al. (2005) looking at fatal car crashes with pedestrians found that Brake Assist alone could reduce pedestrian fatalities by 10 to 12 percent in cases where the driver braked with a maximum braking force of $7m/s^2$. Assuming that non-braking cases usually account of around 40% of pedestrian crashes (Fitzharris and Fildes 2007), this savings would reduce to around 6 to 7 percent of fatal crashes. Other studies of BAS technology reported similar benefits in reduced fatal and serious injury crashes (Hannawald and Kauer 2004; Lawarence et al 2006; Fitzharris and Fildes 2007). This would be expected though as Brake Assist alone is reliant on the driver braking before the crash to gain any benefit. For AEBP, the added benefits of the system self-operating 0.6 seconds before the crash would add additional benefits beyond those from superior braking and account for these differences.

There are just a few studies that have looked at the potential of AEBP to prevent or mitigate pedestrian injuries. A study by Rosén et al (2009) claimed even greater benefits from a case-by-case analysis of German GIDAS in-depth data – a 40% reduction in all fatal and a 27% reduction in serious injury pedestrian crashes using sensors with field of views between 180° and 40° and autonomous brake activation times up to 2 seconds pre-crash. For activation times closer to those used here (0.6 seconds), they predicted effectiveness values closer to those found here (approximately 20% for fatal and 10% for severely injured pedestrian crashes). Furthermore, they did not make any adjustment for road condition and it is questionable if such large pre-crash distances would be realistic for drivers who did not brake.

Robinson et al. looked at the British data to estimate the potential of AEBP in preventing pedestrian injuries. They considered a generic system that brakes automatically when a pedestrian is detected, without any prior warning strategies. The system operates in good light conditions, excluding nighttime crashes and crashes occurring in the fog, snow or rain. It works in an un-cluttered environment and on straight roads only. They considered three different systems, the first one acting at a maximum 2 seconds prior to impact, the second one at 1 second and the third one at 0.6 second prior to impact. The system activates at any speed and deceleration is supposed to be a uniform 0,7 m/s^2. Depending on assumptions, results show a potential of reductions of pedestrian serious injuries around 50 % for first system, 45 % for system 2 and 20 % for system 3.

An improved method to assess the safety benefits of active safety systems, and especially AEB pedestrian, has recently been proposed but not yet applied (or published) (Schramm et Roth, 2009). It is based on the generation of accident scenarios as well as the simulation of driver behavior but its efficient applicability still needs to be demonstrated. Other studies have generated accident scenarios or accident clusters either to identify typical crashes that might be concerned by an AEBP or to propose tests to assess their performance (Lenard et al, 2011; Niewöhner et al, 2011; aspecss EU-funded project). For Lenard et al, a baseline scenario is where a pedestrian steps out from the kerb without obstruction of the driver’s line of sight. A second one is where the pedestrian is smaller and at least partially obscured. A third scenario occurs in adverse meteorological conditions with adult pedestrians. Niewöhner et al. reported about the outcomes of the vFSS working group (Ad**v**anced **F**orward looking **S**afety **S**ystem). The target of the group is to develop proposals for test procedures for forward-looking safety systems based on the results of accident analysis.

Niewöhner et al. propose a classification of main pedestrian crashes into 6 main configurations: first scenario considers a car moving ahead at around 50 km/h that is hitting an adult pedestrian that crosses from the right at a normal pace. The driver reacts and brakes. The second one considers a car moving ahead at around 60 km/h, which is hitting a child crossing from the left and running. The driver reacts and brakes. This scenario frequently occurs at dusk/dawn. These are the two principal scenarios out coming from the vFSS and cover two-third of all severe or fatal injuries caused by a frontal collision with a passenger car. More than 40 % of pedestrian crashes involve an obstruction, most of them being a vehicle. One third of car drivers do not brake. Based on the accident analysis, the group proposed 4 test procedures based on whether the crossing pedestrian is an adult/child, whether he is obstructed or not. They also propose initial velocities of cars, velocities of pedestrian dummies and distance of visibility by the driver of the crossing pedestrian.

Other Aspects on the Analysis

It should be pointed out that the benefits obtained in this study did make a number of assumptions: in particular, that these full benefits would apply for 100% market penetration of the technology, that drivers would not attempt to interfere with the system, that the deceleration levels specified were adhered to in its operation, and that the system is fully functional (no allowance was made for any sub-optimal functioning of the technology).
In addition, the results reported here only considered benefits to pedestrian crashes. It is conceivable that the technology may have additional benefits in other crash modes too, such as frontal and side impact collisions with other vehicles(Chauvel et al, 2012)(but the technology for these crash types is not yet mature). While to date, it appears that the only current system with the necessary sophisticated sensors seem to be that offered by the Volvo XC60. This is likely to change in future. Any benefits in other crash would potentially increase the benefits of the AEBP technology over that reported here and warrants further research.

Finally, this analysis focused on the benefits to crashes that occurred in France alone, based on the patterns of crashes in that country. Other European or international countries have likely to have different crash patterns that will influence the benefits reported here. Ultimately, the real benefits of AEBP technology will only be confirmed from a post-production validation analysis, based on real-world crashes which needs to be undertaken in future research.

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POTENTIAL BENEFITS OF AUTONOMOUS EMERGENCY BRAKING BASED ON IN-DEPTH CRASH RECONSTRUCTION AND SIMULATION

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ABSTRACT

The objective of this study was to estimate the potential effectiveness of AEB systems using simulation of crashes drawn from Australian in-depth crash data.

104 crashes that occurred within 100 km of Adelaide, South Australia, were used to assess the potential effect of AEB systems. The crashes had been investigated at the scene, re-constructed to determine collision speeds, and in this study they were analyzed using simulation to estimate how collision speeds and injury risks would have been modified by each of several AEB systems considered.

Crash types considered were rear-end, pedestrian, head-on, right angle, right turn and a proportion of hit-fixed-object crashes. Other crash types were thought to be less responsive to the effects of AEB and were not considered.

The variation in AEB systems were described using several parameters: the range of the forward-looking zone, the angle or width of the forward-looking zone, the processing time for the system to respond to the road user or object in its path (latency), the time-to-collision (TTC) at which the system would intervene, and the strength of the intervention (the level of braking). The AEB simulation used information from the trajectory of vehicles in the 104 crash reconstructions to estimate what difference each system would have made to the collision speed in each case and for each AEB system considered. Injury risk curves were used to estimate changes in fatal and injury crash risk in each case.

The reductions in risk were weighted according to the rate of crash involvement of vehicles, based on the patterns of crashes in New South Wales for years 1999-2009.

The overall reductions in risk produced by the various AEB systems were substantial. Systems were predicted to reduce fatal crashes by 20-25% and injury crashes by 25-35%. Note that these estimates rely on assumptions about universal operability and reliability of systems.

INTRODUCTION

Autonomous Emergency Braking (AEB) is one of a number of new safety technologies that has emerged in recent years. Such systems have the potential to deliver substantial road safety gains through assisting drivers to detect and respond to hazards through the optimization of braking. Normal emergency braking entails the driver to become cognizant of, and to react to the hazard by applying the brake of braking (and/or steering). AEB promises to be highly effective, as it should effectively reduce average cognition/reaction periods, and hence commence braking the vehicle sooner than a driver would find it possible to do, with optimum brake pressure.

An AEB system is made up of three key components; sensors to detect and classify objects in front of the vehicle, a control system to interpret the data from the sensors and decide when to intervene, and a braking system that allows the vehicle to be braked autonomously. The performance of a particular AEB system will rely on the performance of these three elements.

At this stage, there are several versions of AEB systems and the performance of each system is likely to vary; it would be expected that their performance will improve as the technology evolves. It is important therefore that the influence of each aspect of AEB performance on overall effectiveness can be established, and one method of doing so is through the simulation of many kinds of accident scenarios.

If forward collision avoidance technologies are effective, it be will be because some crashes will be avoided and others will occur at reduced impact speeds. The mechanism of the effect is largely predictable: as mentioned above, braking is optimized and effective reaction times are reduced. Both these effects reduce stopping distances, and the speed of the vehicle at any given point along its stopping path.

Because the mechanism is predictable, the effects of AEB systems are amenable to simulation. Consider a crash that has been investigated at the scene. If the paths of vehicles (or other road users) in a collision are known, the collision can be described mathematically in terms of vehicle speeds, trajectories and the timing and strength of braking (the latter based on scene evidence and/or assumptions about human response to emergency situations). Once the crash is thus described, AEB effects can be superimposed on the collision, and the effect of the AEB system on the collision speed can be simulated. Several investigators have used such an approach before to demonstrate benefits (e.g. Rosen et al., 2010; Sugimoto and Sauer, 2005; Georgi et al., 2005). Other methodologies have also suggested substantial benefits of AEB (Coelingh et al., 2007; Grover et al., 2008; HDLI 2011; Hummel et al., 2011; Kusano and Gabler, 2010; Lindman et al., 2012; Najm et al, 2006).

The objectives of this study were to estimate potential benefits of AEB in all injury and fatal crashes, by considering how it would have affected representative sample of crashes that had been investigated in-depth and at-the-scene.

A more comprehensive report on this study is available (Anderson et al., 2012).

METHODOLOGY

The process by which estimates of the benefits of AEB systems were made in this study is described in Figure 1. The process was as follows:

- Mass crash data was used to select the most common injury and fatal crashes that are relevant to AEB systems
- Crashes that had been investigated in-depth were selected to represent the relevant crash types found in the mass data
- The selected in-depth crashes were reconstructed and simulated to determine trajectories and closing speeds
- The specification (general performance) of AEB systems was parameterised.
- A collision detection and intervention model based on these parameters was applied to the simulations to determine how closing speed would be affected by an AEB system
- Average risk reduction in each crash type was estimated based on a relationship between closing speed and the risk of being injured or killed.

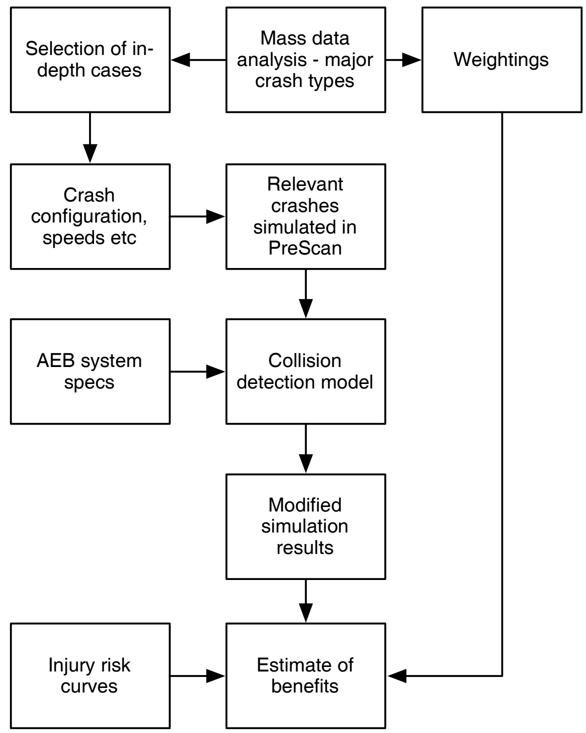

Figure 1. Methodological flow of calculating the safety benefit of AEB systems

Identification of relevant frontal collision crash configurations

Crashes that occurred in New South Wales between 1999 and 2009 causing injury or death were analyzed. Note that NSW crash data do not differentiate severity of injury in non-fatal injury crashes.

Crashes were grouped into similar types with respect to likely AEB effects, noting that little or no effects are expected for some crash types.

Proportions of crashes (injury and fatal) falling into each crash of several crash types were ranked. The top six categories were chosen, which covered approximately 90 percent of all crashes. Table 1 gives the percentages; those crash types that are most relevant to AEB systems are indicated by an asterisk.

These categories were used as a basis to select in-depth crash study cases for simulation. The percentages of all crashes that these crash types represent were also used to weight the results of the simulations, so that an estimate could be made of the overall effect of AEB systems on all crashes.

Table 1
Percentage of crashes within each crash group selected for simulation, disaggregated by speed zone group and severity

Crash Group	Speed Zones					
	50 and 60 km/h		70, 80 and 90 km/h		100 and 110 km/h	
	All injuries	Fatal	All injuries	Fatal	All injuries	Fatal
Intersection*	29.3	9.5	20.2	10.4	4.2	3.5
Rear end*	23.1	-	31.5	2.6	9.4	-
Pedestrian*	14.9	36.0	3.7	15.4	-	4.4
Hit fixed object*	15.5	30.9	22.8	34.7	46.0	41.1
Loss of control	-	3.6	-	-	12.3	7.1
Manoeuvre	4.7	2.7	-	-	-	-
Side swipe	-	-	4.9	2.5	-	-
Head on*	3.6	11.7	6.5	27.9	9.0	33.6
Off Path	-	-	-	-	8.3	3.6
Total	91.2	94.4	89.4	93.5	89.2	93.3

In depth crash data

The Centre for Automotive Safety Research (CASR) has an ongoing at-the-scene in-depth crash investigation activity in South Australia. Approximately 50 to 100 crashes are investigated annually, and a large database of crashes has been compiled over recent years.

A selection of crashes from CASR's in-depth crash investigation database was assembled to represent the circumstances of all crashes in the AEB relevant categories.

A total of 104 crashes were chosen for simulation. The number of cases in each crash type is given in Table 2. Twenty-one were fatal crashes and the remaining 83 were injury crashes requiring ambulance transportation.

Simulating the crash circumstances

Use was made of software called PreScan (Tass, Netherlands). PreScan is a simulation environment for primary safety technologies. The trajectory, speeds, braking and impact configuration of the vehicles in the selected in-depth cases were modeled in PreScan. While PreScan is capable of performing very detailed simulations of advanced driver assistance systems, these capabilities were not used in this study. Rather, PreScan was used to generate a time-based trajectory of the struck vehicle in the coordinates of the primary vehicle. This plot was then used as a basis for determining changes in closing speed with the inclusion of an AEB system in the primary vehicle.

Table 2
Number of simulated cases by crash type and speed zone group

Crash Group	Speed zones		
	50 and 60 km/h	70, 80 and 90 km/h	100 and 110 km/h
Intersection	15	11	10
Rear end	8	1	2
Pedestrian	12	2	1
Hit fixed object	8	4	16
Head on	5	4	5
Total	48	22	34

An example of how an in-depth crash investigation case was modeled in PreScan is shown in Figure 2. The site diagram from the crash is shown at the top of the figure and scenario modeled in PreScan is shown at the bottom. The colored lines in the PreScan diagram represent the trajectories of the vehicles with the spacing of the colored symbols representing the speed of the vehicle.

AEB system modelling

For each crash, the trajectory data was analysed to determine how the closing speed at the collision point might have been affected by an AEB system. To do this, a model of an AEB system was developed for which performance parameters could be specified. The parameters that were used to define the performance of the system were scan geometry, range, angle, computation time, time-to-collision (TTC) action time, system deceleration level and driver supported deceleration level.

- The *scan geometry* refers to the shape of the area in which objects can be detected.

- The *range* and *angle* define the area forward of the vehicle in which an object can be detected. In the case of a rectangular detection area *width* is used in place of *angle*.

- The *computation time* (in seconds) was used to represent the time required by the system to observe an object and predict its future motion.

- *TTC action* dictated the time before the predicted collision that the AEB system applied the brakes.

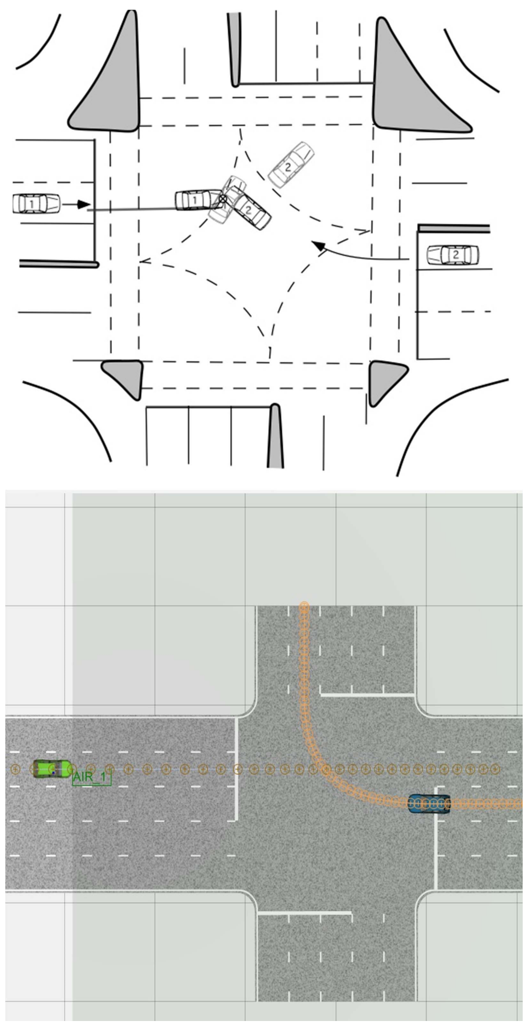

Figure 2. Site diagram of in-depth crash investigation case (top) and corresponding PreScan scenario (bottom)

- The *system deceleration* defined the level of deceleration applied autonomously.

- Most systems will also assist with the braking actions of the driver; if the driver brakes after a potential collision has been detected then their deceleration is increased to the maximum possible. In the reconstruction of the crashes, average driver activated emergency braking of 0.7g was assumed. The driver supported deceleration level in the AEB model was 0.8g. (Note that some AEB manufacturers claim to provide up to 1.0g braking, and although we accept that this is possible over some period of braking, we opted for a more conservative increase in average braking level over the stopping distance).

During the simulation, when a vehicle/pedestrian enters the detection area of the AEB equipped vehicle the model waits for the computation time to expire then calculates predicted positions of the crash partner into the future, in both the longitudinal and lateral direction, based on the object's current position, velocity, and acceleration in the host vehicle's reference frame. If a collision is predicted to occur within the TTC action time, the system brakes the vehicle at either the system deceleration or the driver supported deceleration, depending on the driver's response at that point in time in the real crash.

The parameters used to describe the different systems are shown in Table 3 and a visual representation of the detection areas are shown in Figure 3. The first set of parameters describes a baseline system with a long field of view, a two-second TTC action time and strong emergency braking. This is likely to be most effective but may also produce a relatively large number of false alarms. The second and third systems describe variations of the baseline: one with a shorter TTC and the other with a lower level of braking. The fourth system describes a shorter range, short TTC system with a field of view that has been restricted to only look at the lane ahead; such a system minimises false alarms. It should be noted that this system uses a simplified collision prediction method that is only based on the longitudinal position and velocity of the crash partner, and did not track the path of the crash partner in order to estimate its future path. This simplified prediction method was the basis for selecting a computation time that was lower than other systems.

The AEB system model was only applied to the primary vehicle in the crash. This was the vehicle that had the most 'frontal' collision in the crash. If both vehicles in the crash had a frontal collision (i.e. a head on crash) the vehicle that was travelling straight ahead and had not crossed the centre-line of the road was chosen as the primary vehicle with the AEB system. The results are therefore conservative, with respect to a scenario in which both vehicles are equipped with an AEB system and in which both vehicles can respond.

Table 3
Attribute values for AEB systems modelled

Attribute	Baseline	Short TTC	Low system deceleration	Restricted view
Shape	Cone	Cone	Cone	Rectangle
Range (m)	100	100	100	40
Angle (deg) or width (m)	15	15	15	4
Computation time (s)	0.2	0.2	0.2	0.1
TTC action (s)	2.0	1.0	2.0	1.0
System deceleration (g)	0.8	0.8	0.4	0.8
Driver supported deceleration (g)	0.8	0.8	0.8	0.8

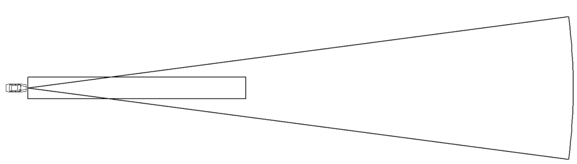

Figure 3. Fields of view of the AEB systems modelled: rectangle and cone

It should be noted that no vehicle dynamics were taken into account once braking began. That is, the model simply calculated the new travelling speed at the original collision point. Because of this, crashes where a change in trajectory might have prevented a collision from occurring were not identified as such. Intersection crashes where a vehicle is travelling across the path of another vehicle are most likely to be affected by this limitation. Note also that the crash phase was not simulated, and hence changes in velocity due to the crash and other crash parameters were not estimated explicitly.

Modified crash speed estimation

The metric that was used to examine the effect of the AEB system is the longitudinal closing speed at impact from the reference frame of the vehicle that is equipped with an AEB system. This was done to properly illustrate the severity of the impact across all configurations. This is referred to as 'impact speed' for simplicity.

The modified relative impact speed at the collision point was calculated as shown in Equation (1), where S_f is the impact speed, S_i is the initial relative speed, A is the deceleration value in units of g, and D is the distance over which the deceleration occurs.

$$S_f = \sqrt{S_i^2 - 19.62AD} \qquad (1)$$

Estimating the reduction in injury risk based on reduction in impact speed

Each crash was scrutinised to determine the predicted effect of the AEB system being considered. For each of the individual crashes there were two relevant variables: impact speed and crash injury outcome. In some cases, the AEB system is likely to result in the crash being avoided. In that case, the effect is trivial to estimate. But in many other cases, the crash is not avoided, but mitigated through a reduction in impact speed, and here the effect on injury needs to be carefully evaluated.

Vehicle occupant injury risk is usually posed in terms of the change in speed during the crash: the delta-v. The delta-v is a function of the closing speed in a collision, the masses of both vehicles and the coefficient of restitution in the collision. As the simulations in this study only predicted a closing impact speed, a general relationship between delta-v and impact or closing speed was used to estimate changes in risk in each crash. For computational simplicity, the delta-v in the longitudinal axis of the primary vehicle was used to assess risk.

Average relationships between impact speed (as defined in this study) and delta-v were determined from CASR's in-depth crash reconstructions. The details of these reconstructions are not given here, but several hundred reconstructions have been performed based on matching simulated vehicle trajectories to forensic data at the scene, using the crash reconstruction software SMAC and HVE. Considering a number of crash configurations and generalising, the following relationships were derived for the vehicle occupied by the most injured person.

- Head-on collisions
  - Delta-v = 0.5 x impact speed
- Hit fixed object
  - Delta-v = impact speed
- Intersection
  - Delta-v = 0.6 x impact speed
- Rear End
  - Delta-v = 0.6 x impact speed

Previous studies have attempted to quantify the relationships between impact speed or delta-v and the average risks of injury and death. These relationships provide a means of estimating the effects of AEB on fatal and injury crash risk in an individual case, and on average: in individual crashes where the speed and severity are known, the curves can be used to estimate the risk that the crash will be as severe, given a reduction in impact speed, and also to estimate the risk that the crash will fall into a lower severity category.

The curves that describe the risk of injury to a vehicle occupant are given in Figure 4. These curves are derived from NHTSA (2005) to cover the categories of injury severity used in this study.

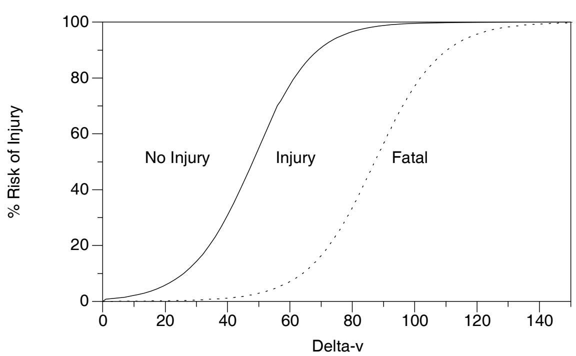

Figure 4. Maximum occupant injury risk curves derived from NHTSA (2005), showing the proportion of no injury, injury and fatal expected at each delta-v.

Pedestrian injury risk is usually expressed in terms of impact speed. The risk curves used in this study are based on Davis (2001) and are shown in Figure 5.

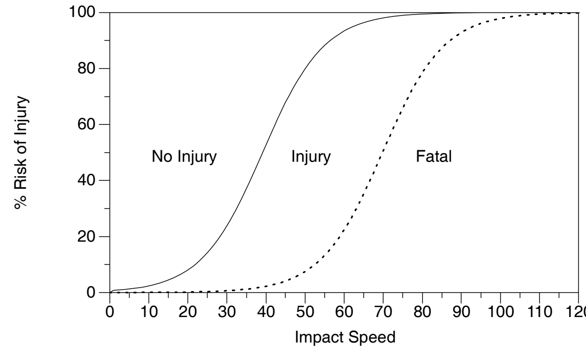

Figure 5. Injury risk curves adapted from Davis (2001), showing the proportion of no injury, injury and fatal expected at each impact speed.

The process for determining the effect of AEB on an individual crash was as follows:

- For occupant injury crashes, the actual crash closing speed was converted to a delta-v in the vehicle longitudinal direction.
- The probability of fatality, injury or no injury was determined from the appropriate risk functions.
- The effect of AEB on the crash was simulated
- For occupant injury crashes, the new closing speed was converted to a delta-v in the vehicle longitudinal direction
- The probabilities of fatality, injury or no injury were "redistributed" based on the revised delta-v (or impact speed in pedestrian crashes) and the original crash severity

For the redistribution of injury risk it was assumed that the crash would either remain in its original category of severity, or be reduced in severity, and that the probabilities of either of these outcomes are given by the original impact speed, the reduced impact speed and the risk curves illustrated above. The equations for doing so are not included here, but note that the usual result was that, for example in the case of a fatal crash, the fatal risk in the original crash (=1) was redistributed between a fatal risk (a) and a non-fatal injury risk (1-a). In some cases, speed was reduced to the point that a probability of no injury was also estimated.

This process was applied to each individual crash and for each variant of an AEB system considered. The individual probability outcomes in each crash were then averaged for each particular crash group and speed zone group.

RESULTS

Position of vehicles at critical times-to-collision

As a preliminary step, the locations of the crash partners at two seconds TTC and one second TTC were plotted for each crash. These are shown in Figure 6. Over-plotted on this data are areas corresponding to certain fields of view. The shaded areas correspond to widths of 4 and 6 metres. For a crash speed to be reduced toby the maximum extent possible, the crash partner must be in the field of view of the system at the relevant TTC action time plus any computation time. It might be noted how the position of the crash partner varies by crash type.

Figure 6 is useful as it illustrates the ranges and the angles of view required for a system to be sensitive to potential crashes. However, Figure 6 also hints at the limitations that AEB systems will have in preventing some crash types. For example, it would be ideal if an AEB system could warn of an impending head-on collision at two seconds TTC. But Figure 6 suggests that this is unlikely to be possible, given the crash partner was typically in its correct lane at two seconds TTC. Even at one-second TTC, the majority of the head-on crash partners are not yet in the forward path of the host vehicle. One of the challenges for the designers of AEB systems is likely to be successfully identifying crash threats from benign traffic in these kinds of circumstances. Trajectory tracking may assist in this, but it will be important to demonstrate that threats can be identified with high sensitivity and specificity.

Effect of AEB systems on crash speeds

The effect of the various AEB systems are summarised in Figure 7, which shows the average impact speed for each crash type according to AEB parameters.

Not all crash types were affected equally. AEB systems had a lesser effect in right angle crashes, whereas relative and absolute speed reductions were larger in other crash types. Pedestrian crash speeds were lower, but a detailed examination of those cases found that crashes in which the pedestrian was obscured prior to the crash were not affected except in the case of the restricted view system. The effectiveness of the restricted view system is due to a combination of a wider field of view at very close range and a shorter computation time. The relative effects of a shorter TTC and lower system deceleration vary between crash types.

The baseline system avoided 19 of 104 crashes while a shortened TTC avoided four. The reduced braking level system prevented 11/104 crashes. The system with a 1.0 s TTC and quick reaction time, but with a restricted view prevented 9 crashes.

The potential of AEB systems to avoid crashes altogether appears to be greatest for pedestrian crashes and rear end crashes, though this will clearly depend on the performance parameters of the AEB system.

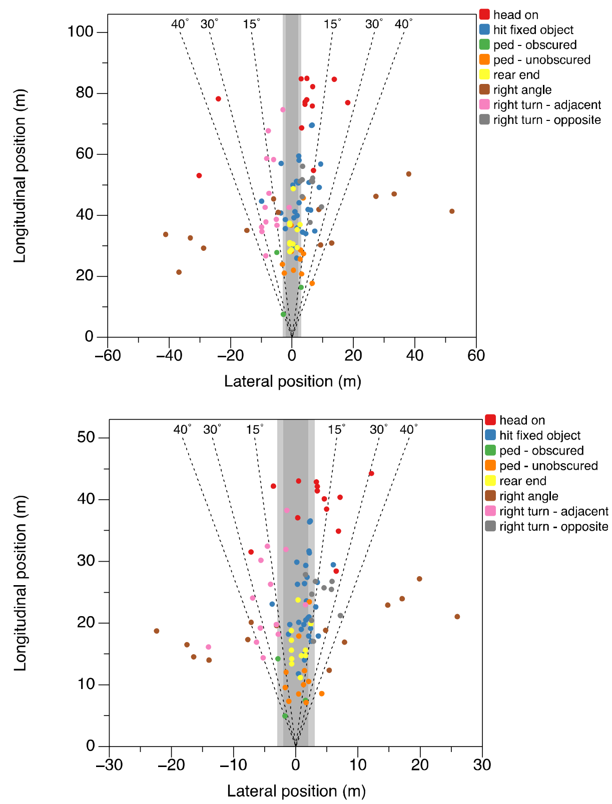

Figure 6. Location of crash partner at two (top) and one seconds (bottom) TTC by crash type

Effect of AEB systems on fatal crash risks and injury crash risks

Estimates of the effect of the speed reductions in each crash were made according to the method described previously:

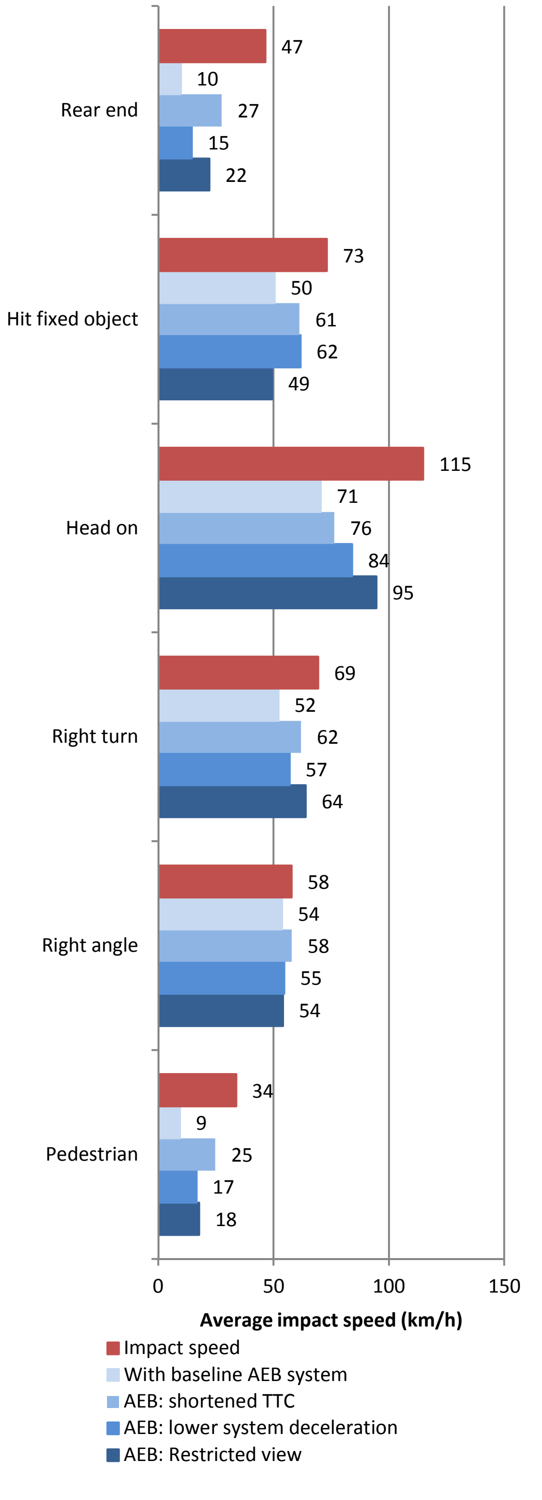

Figure 7. Average impact speeds by crash type and AEB system.

- Risks were modified in each crash as described in the method.
- The changes in risk were aggregated within each category of crash.
- These average changes in risk were then weighted according to the incidence of each crash subcategory in the mass-crash data (see Table 1 for the incidence of each category of crash.)
- The effect on all crashes was then totalled.

The results are shown in Table 4. Reductions are given for fatal crashes and injury crashes separately. Reductions are given as a reduction of all relevant forward collisions (see asterisked crash categories in Table 1) and also of all fatal and injury crashes.

Table 4
Percentage reductions crashes

System	Reduction (per cent)			
	Fatal		Injury	
	Forward crash	All crash	Forward crash	All crash
Baseline system	39	27	51	37
Shorter TTC	23	16	37	27
Lower deceleration	29	20	48	34
Restricted view	34	23	47	34

DISCUSSION

The results presented in this paper add support to other estimates that AEB will have a marked effect on crash risk. Other research has mainly examined effects on rear-end and pedestrian crashes; this study suggests that that AEB might be effective in a broad range of crash types, if systems are developed sufficiently to identify a broad range of potential crash risks.

The models of AEB used in this study are likely to be simplified representation of systems being developed by manufacturers. Hence, we may not have completely represented some current systems; for example, an AEB system may not activate braking until the crash partner is more-or-less directly in front of the vehicle, even if the crash partner is within the detection area. The restricted view system presented in this paper attempts to represent this kind of system, but such a system might be made more effective by preparing the vehicle systems or even applying partial braking before the crash partner is directly in line of the host vehicle. A further simplification we have made is to assume that all the variables included in the model are static. In actual systems they may be dynamic (e.g. TTC may be increased at higher speeds, or reduced in some environments to prevent false alarms).

Nevertheless, these results do indicate that differences in the way that systems operate will make a material difference to their effectiveness, in terms of either speed reductions or injury risk. Reduced TTC and/or system deceleration reduced the effectiveness of the baseline AEB system. A wide field of view at very close range (represented by the rectangular field of view) and low system latency assisted in number of crash scenarios. A reduced TTC and restricted forward view represent potential countermeasures to any potential false-alarm problems with AEB systems. Furthermore, it has been assumed that the systems are active over the entire range of speeds that were extant in the crashes that were simulated.

The restricted view system was generally not as effective as the baseline system. Exceptions were hit fixed object crashes (mainly due to the inclusion of crashes occurring on a straight stretch of road) and right angle crashes. However it did still show average impact speed reductions of 16 km/h or more in all pedestrian, head on, rear end and hit fixed object crashes, and it was the second best system in terms of reductions in fatal and injury risks. These results show that such a system can still be effective in reducing impact speeds in a variety of crash types while avoiding the problems of false alarms that might arise through reacting to objects in a larger scan area.

The reductions in average impact speed found in the rear end, pedestrian crashes and head on crashes are notable. While no head on crashes would have been avoided, the average impact speed was reduced from 114 km/h to as low as 71 km/h. This represents a considerable reduction in impact severity and may result in a much-reduced risk of injury, especially fatal injuries. However, it should be borne in mind that the results pertain to a system that tracks and predicts and responds to an imminent crash even if the crash partner is not directly in front of the vehicle. If the AEB system was designed to react only to objects within the vehicle's lane, Figure 6 shows that the vehicle would not have commenced braking in any of the head on crashes at two seconds TTC, and only to two of the nine at one second TTC. The success of AEB in mitigating head on crashes may therefore be largely dependent upon the ability of the system to correctly discern a threating vehicle before it impinges of the AEB equipped vehicle's lane of travel (as was assumed for three of the four systems evaluated in this analysis).

There are other potential limitations to the performance of AEB systems that were not considered in this analysis. These include the ability to function in low light, the ability to function in inclement weather, and to have high sensitivity to crash potential. The effectiveness levels estimated in this report assume no failures to detect, and therefore need to be tempered by what might be known about system reliability in all crash conditions.

Predicted speed reductions estimated from in-depth crashes are subject to error from various sources, including estimates of speed in the actual crash, but also from the number of crashes in the sample. While we simulated over 100 crashes, the number in each crash type was less than 20 in every case, and the results are correspondingly subject to random error.

The simulation methodology did not account for crashes that may have been avoided due to one vehicle slowing sufficiently to allow the other vehicle to safely pass. This is most likely to affect right angle crashes. Conversely, the possibility that rear end crashes may occur when a second vehicle following an AEB equipped vehicle is not able to brake as quickly or as hard as the AEB equipped vehicle is sometimes raised. In fact, Schittenhelm (2009) found the opposite to be true. He suggested that AEB systems result in earlier, less severe braking, and helped to avoid last moment panic braking that can precede a vehicle being struck in the rear.

CONCLUSIONS

AEB has the potential to reduce the impact speed, and hence the severity, in pedestrian crashes, right turn crashes, head on crashes, rear end crashes and hit fixed object crashes. It appears that they may have little or no effect on right angle crashes, but secondary effects that improve drivers' abilities to avoid collisions may be important in this case. Potential benefits appear to be greatest in pedestrian crashes, rear-end crashes and head on crashes.

The variations in system specification demonstrate the advantages of a longer time-to-collision, higher autonomous deceleration and economical data processing.

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IMPLEMENTATION OF AUTONOMOUS EMERGENCY BRAKING (AEB), THE NEXT STEP IN EURO NCAP'S SAFETY ASSESSMENT

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Paper Number: 13-0269

ABSTRACT
Euro NCAP has released its updated rating scheme for 2013-2016 that outlines, amongst other technologies, the implementation of Autonomous Emergency Braking (AEB) technologies within the overall rating scheme. Three types of AEB technologies will be included in the rating scheme, starting with low speed car-to-car AEB City and higher speed car-to-car AEB Inter-Urban in 2014, followed two years later by AEB Pedestrian.

In 2011 the Primary Safety Technical Working Group (PNCAP TWG) started working on AEB protocols, where Euro NCAP members have contributed to the development of the Test and Assessment protocols. They have been developed in a relatively short time, by finding the commonalities and discussing the differences between different initiatives from industry, insurers and others that were the main source of input to the working group.

Recently, both AEB City and AEB Inter-Urban protocols were finalized. The test protocol details a series of tests, following an incremental speed approach for systems with AEB and Forward Collision Warning (FCW) functionality, and specifies in detail the target vehicle to ensure the highest level of reproducibility and repeatability. The assessment protocols identify the scoring principle and relative weight of each scenario for inclusion in the overall rating scheme. This paper describes both protocols.

BACKGROUND
In 2009, Euro NCAP introduced its new rating scheme [1], which allows new technologies to be implemented in the overall assessment of a new vehicle. The new rating scheme consists of four areas of assessment, also called boxes, which together result in one overall rating. The four areas of assessment are Adult Occupant Protection (AOP), Child Occupant Protection (COP), Pedestrian Protection (PP) and Safety Assist (SA).

With the introduction of the new rating scheme, Euro NCAP also released a roadmap for the years 2010-2015 [2] where the implementation of AEB technologies was outlined. Low speed AEB systems, AEB City, were directly linked to whiplash prevention and therefore added to the AOP box. It is noted that AEB City systems primarily avoid or mitigate whiplash injuries in the opponent vehicle and are seen as partner protection systems. Euro NCAP deliberately does not make a distinction between self or partner protection when appointing technologies to a certain box.
With regards to high speed AEB Inter-Urban systems, these are included in the SA box as their benefits are broad and are not directly related to any of the tests performed in the other boxes.

Euro NCAP Advanced
By opening the rating scheme for new technologies, Euro NCAP also introduced an award system called Euro NCAP Advanced to be able to promote new important technologies, explain their safety potential and learn how they are evaluated by the carmakers themselves. Amongst other technologies, AEB systems from several manufacturers were put forward to achieve such a Euro NCAP Advanced reward. The accident analyses carried out to support their applications suggest that AEB systems could reduce rear end crashes by more than 25%.

AEB Survey
Although the expected benefit of AEB technology is significant, the functionality and availability of AEB in Europe is far from standardized. In 2012, Euro NCAP carried out a survey on the current (per model) market availability of AEB systems within the EU-27. The survey revealed that AEB is still not offered on 79% of the car models on sale in Europe and that 66% of manufacturers do not offer an AEB system on any of their new car models. The survey showed that information on AEB was generally hard to find at manufacturers websites and that there was no consistency in naming between brands. The equipment that was offered was mostly optional, even though there were encouraging signs of serial fitment of AEB City technology on small class cars in particular.

Detailed results can be found on the Euro NCAP website [3].

WORKING GROUP

As for all Euro NCAP protocols, the development was done within a collaborative Working Group. For AEB, the P-NCAP TWG was given the task to deliver a test and assessment procedure by the end of 2012, for implementation in 2014. Although car makers and suppliers were not directly involved in the working group, several meetings were organised between representatives of both sides to discuss the procedures. More importantly, the work of the group took advantage of and brought together the results delivered by several main initiatives in Europe that where looking into the development of AEB test and assessment procedures.

Initiatives

Within Europe, four main initiatives were running in parallel, all with the same goal of developing test procedures for assessing AEB and FCW systems: ADAC, AEB, ASSESS and vFSS.

The German automobile club ADAC, one of the Euro NCAP's member organisations, had developed an inflatable vehicle target to be able to perform a Comparative test of advanced emergency braking systems on high end vehicles [4] with support from automotive first-tier suppliers Continental and Bosch. Their first test series using the target concluded that any of the advanced emergency braking systems tested were capable of significantly reducing the severity of rear-end collisions.

The RCAR Autonomous Emergency Braking group [5], led by Thatcham has the aim of designing and implementing a testing and rating procedure for Autonomous Emergency Braking (AEB) systems reflecting real world accident data. It is hoped that this will encourage the development of AEB systems that can avoid or mitigate the effects of car-to-pedestrian and car-to-car collisions seen in the most common crash types. The group mainly consisted of insurance institutes, supported by Volvo Car Corporation and first-tier supplier Continental.

The European Commission sponsored project ASSESS (Assessment of Integrated Vehicle Safety Systems for improved vehicle safety) led by Humanetics Innovative Systems had specific project goals to develop harmonized and standardized assessment procedures and related tools for selected integrated safety systems [6]. The project partners consisted of nine research institutes, four of which were Euro NCAP laboratories: BASt, IDIADA, TNO and TRL. From industry side, Daimler, PSA and Toyota participated as car manufacturers and Bosch and TRW as first-tier suppliers.

The fourth initiative was vFSS (Advanced Forward-Looking Safety Systems), a German partnership led by DEKRA, in which all German vehicle manufacturers were represented (Audi, BMW, Daimler, Porsche and VW) along with Ford, Opel, Honda and Toyota [7]. Other project partners were insurance institutes Allianz and GDV and the research institute BASt. The aim of the vFSS project was in line with the other initiatives: the development of test procedures for driver assistance systems (in particular advanced emergency braking systems) in order to ensure a robust assessment of such systems.

The outcome and deliverables of all the initiatives were extensively discussed within the working group and formed the basis for the decision on test scenarios and target used.

TEST SCENARIOS AND TARGET

Within the different initiatives, there was a large overlap of the proposed test scenarios, based on an extensive analysis of real world rear-end crashes. Overlaying the proposed test scenarios, the P-NCAP TWG agreed to the following test scenarios for AEB City and AEB Inter-Urban:

AEB City

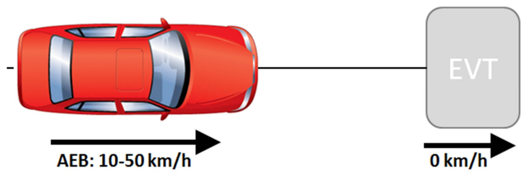

Figure 1. AEB City scenario, CCRs

AEB Inter-Urban

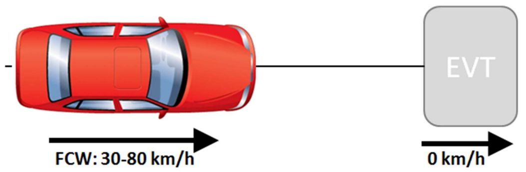

Figure 2. AEB Inter-Urban scenario, CCRs

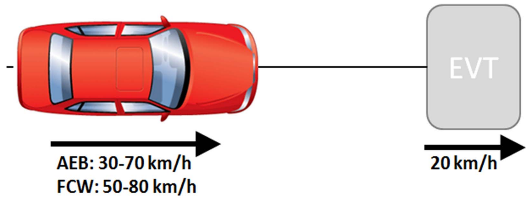

Figure 3. AEB Inter-Urban scenario, CCRm

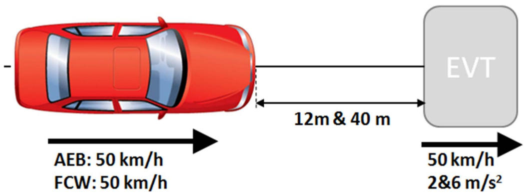

Figure 4. AEB Inter-Urban scenario, CCRb

For the AEB Inter-Urban scenarios CCRm and CCRb, the FCW function tests are performed in case there is no complete avoidance by the AEB function. For the CCRs scenarios, there is no AEB function assessment.
FCW functionality is assessed by reacting to the warning that is issued after an imminent collision has been detected. A brake robot will apply the brakes 1.2s after the warning starts to simulate driver reaction time.

Incremental Speed Approach
The range of speeds shown in the figures above will be tested in an incremental approach. Starting at a very low speed, the approach speed of the Vehicle Under Test (VUT) is stepwise increased by 10 km/h while impact with the Euro NCAP Vehicle Target (EVT) is fully avoided. When there is first contact between the VUT and the EVT, an additional test is performed at a speed 5 km/h lower and testing continues with 5 km/h increments until the speed reduction achieved of the VUT is less than 5 km/h.

Euro NCAP Vehicle Target
Different types of target were studied within the aforementioned initiatives but also by the vehicle manufacturers for in-house evaluation. A number of the most promising targets were evaluated at a number of vFSS events to verify their ability to be seen by different types of sensors and their robustness. It was concluded that the ADAC inflatable target was the preferred target for the moment, based on its sensitivity to current generation Radar, LIDAR, camera and PMD sensors. The details of the target are presented by ADAC in separate paper [8]. Euro NCAP adopted this target for its first phase of testing. For this purpose, it has a new cover that matches a real car and was subsequently referred to as the Euro NCAP Vehicle Target.

Figure 5. Euro NCAP Vehicle Target (EVT)

Test equipment and test track
Euro NCAP uses different laboratories for all of its tests. To ensure repeatable and reproducible results now and in the future, the WG decided to set strict tolerances for testing AEB systems, even though it was acknowledged that this may not always be necessary to evaluate the performance of these systems in the scenarios described earlier. The tolerances used are listed below:

- Speed of VUT + 1.0 km/h
- Speed of EVT + 1.0 km/h
- Lateral deviation 0 ± 0.1 m
- Relative distance (CCRb) 0 ± 0.5m
- Yaw velocity 0 ± 1.0 °/s
- Steering wheel velocity 0 ± 15.0 °/s

Due to these strict tolerances, all of the Euro NCAP laboratories will use both steering and brake robots to control the vehicle during test. Details on the test execution and the equipment used can be found in a paper by Thatcham, one of the Euro NCAP's test laboratories [9].

Another, less controllable, influencing factor is weather condition. The tracks used for the assessment are spread over Europe with different climates. Although the weather may influence the performance of the systems, it is thought that in day-to-day use these systems also encounter various weather conditions. However, limits are set to temperature (between 5 and 40°C) and wind (below 10 m/s). There may be no precipitation falling and horizontal visibility at ground level must be greater than 1km. Finally, the natural ambient illumination must be homogenous in the test area and in excess of 2000 lux for daylight testing with no strong shadows cast across the test area other than those caused by the VUT or EVT. It is also ensured that testing is not performed driving towards or away from the sun when there is direct sunlight.

ASSESSMENT
The assessment of AEB systems includes three different functionalities: the Autonomous

Emergency Braking function, the Forward Collision Warning function and the Human Machine Interface. For AEB City systems, the FCW function is not taken into account as, for low speeds, warning is not considered effective.
The assessment protocol is able to cope with AEB systems that have AEB (auto-brake) or FCW (warning only) functionality only or a combination of both functionalities. AEB only and AEB/FCW combined systems are able to score full points, whereas FCW only systems can only score the points available for FCW and HMI.

Assessment Criteria
For both the AEB and FCW functionality, the only assessment criterion used is the impact speed reduction. For each run into the target at incremental speed, a full score is given when the target is completely avoided. Where contact occurs, the points are awarded on a sliding scale basis, where the proportion of speed reduction based on the relative test speed determines the proportion of available points scored, until the speed reduction achieved is less than 5 km/h and testing stops.

Score = $[(v_{rel\ test} - v_{rel\ impact})/v_{rel\_test}] \times points_{test}$

The number of points available for the different test speeds is based on accident frequency, where the most frequent speed crashes are given more weight than others. The available point distributions for FCW and AEB for the CCRs and CCRm scenarios respectively are shown in the figures below. The point distribution is based on GIDAS accident data.

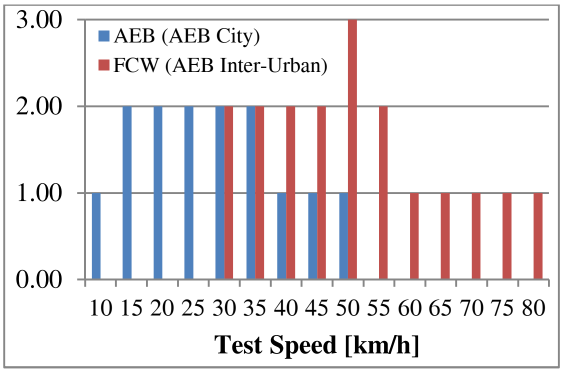

Figure 6. Maximum points per CCRs test speed for AEB (City) and FCW (Inter-Urban)

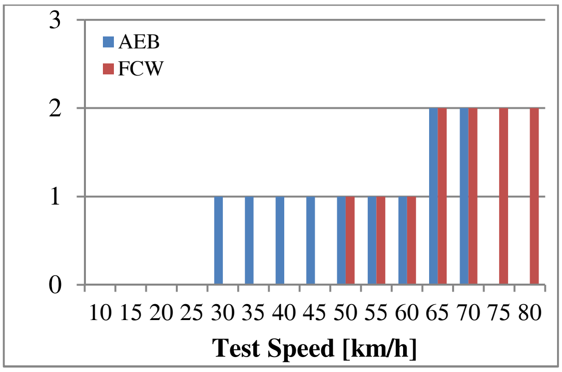

Figure 7. Maximum points per CCRm test speed for AEB (Inter-Urban) and FCW (Inter-Urban)

The points available for the CCRb scenarios for both AEB and FCW functionality are as follows:

Table 1
Available points for CCRb scenarios

	EVT deceleration level		
Headway		**2.0 m/s²**	**6.0 m/s²**
	12 m	1.00	1.00
	40 m	1.00	1.00

Human Machine Interface
The effectiveness of the whole AEB system, both AEB and FCW functionality, highly depends on the HMI of the warning and the ON/OFF rate of the system, especially for the FCW functionality. At this moment, Euro NCAP has not defined qualitative criteria for warning due to the limited knowledge available on this subject. However, some points are awarded to systems that encourage use and offer supplementary warnings.

AEB City
To be eligible for assessment, the AEB City system needs to be fitted as standard to all vehicle models sold within the EU-27. Additionally, the system needs to completely avoid the impact up to 20 km/h.
As for AEB City, only the autonomous emergency braking functionality is considered.HMI points will only be awarded if the AEB system is default ON at the start of every journey. When this condition is met, points are awarded for the ON/OFF switch when this is more sophisticated than a simple "push on a button", e.g. hold button for several seconds, hence discouraging easy disconnection at each journey.

AEB Inter-Urban
The fitment rate requirement for AEB Inter-Urban systems to be eligible for assessment is less stringent than for AEB City. In the first two years 50% of all sales of a vehicle model should have the

system fitted. In 2016 this should be 70%, and in 2017 the AEB Inter-Urban system has to be standard fit.
In AEB Inter-Urban, the AEB and FCW functionality needs to be default ON at the start of every journey, when available. In addition, the forward collision warning must be loud and clear to the driver. When the above conditions are met, HMI points can be scored for the following items:

- Activation/deactivation of AEB and/or FCW Needs to be more sophisticated than just pushing a button once
- Supplementary warning for FCW. In addition to the required audiovisual warning, a more sophisticated warning like head-up display, belt jerk, brake jerk or any other haptic warning is available.
- Reversible pretensioning of belt. When the system detects a critical situation that can possibly lead to a crash, the belt can already be pre-tensioned to prepare for the oncoming crash.

Total Score
For the total score of AEB City and AEB Inter-Urban, the normalized sub-scores (as a percentage of the maximum points available) of HMI, AEB and FCW functionality weighted and summed.

For AEB City:
Score = (AEB x 2.5) + (HMI x 0.5)

For AEB Inter-Urban:
Score = (AEB x 1.5) + (FCW x 1.0) + (HMI x 0.5)

Scoring example for an AEB Inter-Urban system:

Table 2
Example of AEB function test results in CCRm scenario

Vtest [km/h]	Vrel test [km/h]	Vimpact [km/h]	Vrel impact [km/h]	Score
30	10	0	0	1.000
35	15	0	0	1.000
40	20	0	0	1.000
45	25	0	0	1.000
50	30	30	10	0.667
55	35	45	25	0.286
60	40	55	35	0.125
65	45	-	-	0.000
70	50	-	-	0.000
Total				**5.078**
Normalised				**46.2%**

AEB function in CCRb scenario: 67.5%

AEB score = average(CCRm,CCRb)
= 56.9%

FCW function (assumed normalized scores for this example)

- CCRs scenario: 84.7%
- CCRm scenario: 76.4%
- CCRb scenario: 100.0%

FCW score = average(CCRs,CCRm,CCRb)
= 87.0%

HMI score:
Prerequisites not met. System can be switched OFF with a single push on a button.
AEB Inter-Urban total score:
(AEB x 1.5) + (FCW x 1.0) + (HMI x 0.5)
56.9% x1.5 + 87.0% x1.0 + 0% x0.5 = 1.724 points

Finally, the AEB scores are included in the overall rating for the vehicle. The AEB City scores are awarded in the Adult Occupant Protection box and the AEB Inter-Urban scores are awarded in the Safety Assist box.

DISCUSSION
With the introduction of a relatively simple test to assess advanced systems like AEB, Euro NCAP wants to push the introduction of these systems into the market. From the start of the development of the protocols, it was clear that there would be a revision of the protocol within a couple of years.
The target used during the tests represents only half a car's length and can only be used in non-offset car-to-car rear scenarios. In addition, the target is relatively easy to identify and can be seen as an overrepresentation, especially for radar systems. As sensor systems get more advanced, the target should align better with the vehicle it is representing.
For the moment, only rear end impacts are included, where it is foreseen that systems will advance rapidly and more scenarios can be added, which can be more challenging in the next phase.
The requirements for HMI are very basic and these requirements will be reviewed in the next years when a number of systems are assessed and best practice is identified.
All in all, Euro NCAP will continue to develop the requirements for AEB technologies to keep up with the development of these technologies and to ensure high quality systems for consumers.

CONCLUSIONS
In 2014 Euro NCAP will start assessing both AEB City and AEB Inter-Urban systems, which are taken into account in the Adult Occupant Protection and Safety Assist boxes respectively. The assessment is based on three functionalities; AEB, FCW and HMI.
The working group will continue to develop protocols for AEB pedestrian and an extension of the AEB City and Inter-Urban protocols.

ACKNOWLEDGEMENT

The P-NCAP working group was able to deliver the test and assessment protocols in time for implementation in 2014 due to all the hard work done within and outside of the working group.

P-NCAP WG members

ADAC, BASt, DEKRA, Department for Transport (DfT), IDIADA, NL-MOT/RDW, Swedish Transport Administration (STA), Thatcham, TNO and UTAC

Euro NCAP wants to thank the OEMs and suppliers for their support and feedback on the protocols and all the members of the P-NCAP WG for all effort and resources they put into the development and verification of these protocols.

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MUNDS: A NEW APPROACH TO EVALUATING SAFETY TECHNOLOGIES

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ABSTRACT

Real-world evaluations of the safety benefits of new integrated safety technologies are hampered by the lack of sufficient data to assess early reliable benefits. To address this, a new approach was developed using a case-control, meta-analysis of coordinated national police data from Australia, Finland, Italy, New Zealand, Sweden and the UK, in assessing the benefits of Electronic Stability Control (ESC). The results showed that single-vehicle injury crash reductions varied between 21% and 54%, dependent on the speed zone of the crash and the road condition (significantly more effective in wet/icy road conditions than dry roads). For injury crashes involving more than one vehicle, ESC was twice as effective preventing crashes in high speed than lower speed zones. The findings using this new approach were consistent with those published by various equivalent individual studies, bearing in mind their wider international scope in terms of driving conditions and vehicle fleets studied. It was concluded that this new approach using a "prospective" meta-analysis method has the potential to expedite the process of evaluating emerging vehicle safety technologies that would otherwise be subject to much greater delays before sufficient evidence could be collected.

INTRODUCTION

The evaluation of the safety benefits of new integrated safety technologies using real-world crash data takes considerable time for sufficient crash data to become available, given the slow take-up rates of new vehicles in the vehicle fleet, and improved crashworthiness and roadworthiness (Sabow, 1994). Estimates from evaluation studies carried out across individual countries suggest that it can take at least 5-years for sufficient data to accumulate to permit a robust statistical analysis of the safety effects, and even longer for technology with a relatively narrow application to particular crash types. Given the pressing need for governments, manufacturers, and community groups to know how effective integrated safety technologies are in terms of preventing crashes and serious injuries, a new approach was desperately needed to provide early reliable evidence of the real-world effectiveness of these technologies.

Meta-Analysis

Meta-analysis has been defined as a "systematic method of evaluating statistical data based on the results of a number of independent studies of the same problem" (Medical Dictionary, 2013). They note that Meta-analysis has the advantage that it can produce a stronger conclusion than that of any individual study (ibid). In classic use, meta-analysis combines the findings of various existing published studies on a common theme. While the approach has been used in the medical arena for many years (eg, Cochran Collaboration, 2013) the approach has also recently been used in evaluating ESC in vehicles by Erke (2008) and Høye (2011). While meta-analyses is useful in assessing clinical and vehicle safety improvements, the approach relies on assembling already published in the scientific literature ***retrospectively***, and thus is subject to long delays due to the publishing process.

An alternative meta-analyses approach would be to initiate a collaborative study involving the assembly of a number of independent aggregate analyses from several countries ***prospectively***, using a common study design. This brings together a much larger pool of data than any one country has available and speeds-up the process of evaluating safety technologies. Furthermore, it would provide a more internationally relevant and detailed assessment of the safety benefits than any one single country can provide. These were the motivations for setting up the MUNDS (**MU**ltiple **N**ational **D**atabase **S**tudy) programme.

The MUNDS Approach

Researchers, government officials and auto manufacturers came together to develop a new prospective meta-analysis method for assessing the safety benefits of vehicle technologies. It was apparent that the only way in which these analyses could be undertaken more quickly using national crash data was to expand the availability of these data.

The MUNDS objectives were two-fold. First, to see if such an approach was feasible and valid, and second, to demonstrate the benefits in terms of time saved and additional insights from the approach.

METHOD

National data from Australia, Finland, Italy, New Zealand, Sweden and the UK were available, involving crashes of light passenger vehicles manufactured between 2000 and 2010. While the fitment of ESC is not routinely coded in national crash data, supplementary records were used by each country to identify those fitted with ESC in their databases. Only records where ESC was or was not definitely confirmed were included in the analysis.

Given that those who own or manage crash databases could not provide individual case records, the MUNDS team structured a series of blank summary tables containing the relevant data for the multivariate analysis which were sent to each data provider for them to complete and return. These tables and associated details were forwarded to the MUNDS statistician who then combined them as input for a series of overall analyses.

Different severity thresholds for recording crashes were identified and the highest common threshold was chosen to overcome potential difficulties with the analysis. Independent variables included vehicle size and type (small, large or SUV), year of manufacture, driver age, driver injury, crash type (frontal, side or rear-end), single or multiple vehicle collision, speed zone (above or below 75km/h), road condition (dry, wet or snow) and whether ESC was fitted or not.

Modelling Procedure: These compatible data were then pooled to enable statistical models to be developed, using logistic regression. Estimates were adjusted for the independent variables that could confound estimates of ESC effectiveness such as vehicle ages, types and sizes; road conditions, and driver age.

Quasi-induced exposure methods (Keall and Newstead, 2009) were used where counts of rear-end crashes represented a measure of exposure to risk of an injury crash. Logistic models were fitted to an outcome variable where Y=1 were crashes that excluded rear-ends, and Y=0 involved a rear-end crash. The odds of a non-rear-end crash using this data set are equivalent to the *risk* of non-rear-end crash involvement. These risk estimates could then be derived directly from the estimated coefficients generated by fitting the logistic models.

Explanatory variables included whether ESC was fitted or not, country; year of manufacture, vehicle type; driver age, speed zone, road condition, and any significant interactions between these factors. The interaction terms and other covariates served to control for potentially confounding effects that could otherwise bias the estimates of ESC effectiveness. The "forwards-selection" approach was used where one variable was added at a time to the model until a point was reached where no remaining variable made a significant partial contribution to predicting the odds of a non-rear-end crash.

The final models all fitted well, with no problems indicated by Hosmer-Lemeshow (2000) goodness-of-fit statistics. There was some modest over-dispersion, symptomatic of some degree of clustering of the observations or heterogeneity within classes. This was allowed for by estimating an over-dispersion factor by using quasi-likelihood estimation in the model fitting.

RESULTS

The results section is structured into two distinct sections. The first shows the results for the various country databases together with the time benefits of the approach, while the second outlines the findings for ESC and the validation of the approach.

Efficacy of the MUNDS Approach

The individual country findings obtained from the various countries is shown in Table 1 below.

Table 1: ESC numbers and benefits for all injury crashes (excluding rear-ends)

Country	Total Cases	ESC Fitted	ESC Benefit*	95% CI
Australia	25,571	1,247	-4%	(-21%, 10%)
Finland	3,989	343	1%	-43%, 32%)
Italy	**19,648**	**14,614**	**19%**	**(11% ,26%)**
NZ	3,022	194	-3%	(-55%, 32%)
Sweden	**17,739**	**4,880**	**29%**	**(22%, 35%)**
UK	31,114	7,172	3%	(-4%, 10%)
Overall	**101,083**	**28,450**	**13%**	**(9%, 17%)**

**A negative value indicates an increase in the crash rate*

While there were differences in the number of cases and their data periods, most showed positive benefits in ESC fitment (Australia and NZ were exceptions). The overall effect was a 13% significant reduction in injurious crashes with narrower confidence intervals.

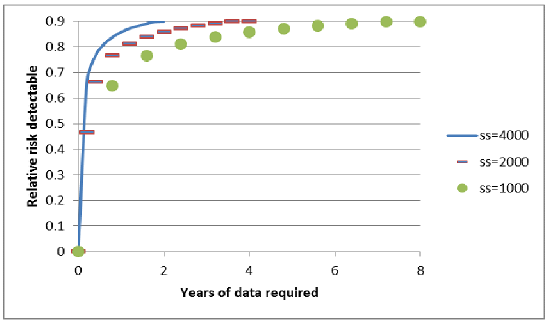

Figure 1: Time savings using the MUNDS approach

These findings show that while the estimated individual country benefits were not all statistically significant, the overall results were. This is essentially a consequence of smaller sample sizes for some countries individually, compared with the larger numbers overall obtained from using the prospective meta-analysis approach.

Figure 1 shows the number of years (and data) needed for a study to detect a 10% improvement in risk (a relative risk of 0.9) for three different sample sizes, which could feasibly be from three different sized countries with the specified numbers of crashed vehicles fitted with the technology. The country with the smallest prevalence of these crashes of interest (sample size=1,000) would take eight years to detect a safety benefit, compared to only two years for the study involving 4,000 crashed vehicles of interest. This latter larger study could be considered to be a MUNDS-type analysis in which the data from several countries are pooled.

Both these sets of results confirm the efficacy of adopting a prospective meta-analysis. The next set of analyses show the benefits of ESC for the independent variables under examination in the MUNDS analysis.

ESC Benefits (Single Vehicle Crashes)

As noted earlier, adopting a prospective meta-analysis procedure was expected to enable a more comprehensive set of results, given the additional power associated with the combined database. These estimates are presented by vehicle size, road conditions and speed limit (crash severity).

Table 2: Crash reductions in single-vehicle crashes where driver was injured

Crash Factor	Crash risk ESC Vehicle	Crash risk for non-ESC vehicle	Estimated crash (risk) Reduction	95% confidence limits
Dry roads	0.157	0.225	30%	(23%, 37%)
Wet/snow/ice	0.274	0.489	44%	(36%, 51%)
Speed Limit <75km/h	0.182	0.241	25%	(16%, 32%)
Speed Limit ≥75km/h	0.286	0.547	48%	(41%, 54%)
Small cars	0.168	0.241	30%	(23%, 37%)
Large cars	0.242	0.405	40%	(31%, 48%)
SUVs	0.222	0.462	52%	(30%, 67%)

The risks shown in Table 1 are estimated by the relative rates of the given type of single vehicle crash compared to the rates of rear-end crashes for the same vehicle/weather/speed limit conditions. So a lower rate for small cars, for example, indicates they have higher rates of the comparison crash type. This can arise when the vehicle is used more in congested traffic, where rear-end collisions are more common. It is therefore important that the relative risks are used (comparing column 3with column 2 of the table) to control for these different patterns of vehicle usage.

ESC Benefits for the factors of interest

Table 2 shows the findings for the ESC benefits for the three factors road condition, speed limit and vehicle size, included in the modelling. These benefits relate to single vehicle injury crashes only.

Road condition: While there were significant reductions in injury crashes for ESC fitted vehicles for all road conditions, those on wet, icy and snowy roads) were significantly greater as shown in Table 2. This result is consistent with previous studies by Lie et al (2004, 2006) and Thomas (2006).

Speed limit: This factor was included as a proxy for crash severity (higher speed limited areas are more likely to experience higher severity crashes). The findings here confirm that reductions in single-vehicle injury crashes were almost twice those in lower speed limited areas. While Sferco et al (2001), Aga and Okada (2003), and Dang (2004) speculated that the effects of ESC are likely to be greater at higher speeds where vehicle dynamic performance plays a greater part in the crash, this finding has not been previously quantified.

Vehicle size and type: The reduction in injury crashes was significant for both passenger cars and SUV models, but greater as vehicle size increased and for SUVs. Similar findings for vehicle size and type have been previously reported by Dang (2004), Green and Woodroffe (2006), Farmer (2006), Thomas (2006) and Scully and Newstead (2007), consistent with those found in Table 2.

Individual and overall benefits across countries

Table 3: By country: single vehicle benefits by road condition and speed limits

Country	Wet <75km/h	Wet ≥75km/h	Dry <75km/h	Dry ≥75km/h
Australia	12% (-24%,37%)	**43% (20%,60%)**	-8% (-48%, 21%)	**31% (3%, 51%)**
Finland	2% (-49%, 36%)	**38% (5%, 59%)**	-19% (-80%, 21%)	24% (-15%, 49%)
Italy	**38% (25%, 49%)**	**61% (51%, 68%)**	**25% (13%, 35%)**	**52% (42%, 60%)**
NZ	22% (-61%, 63%)	50% (-3%, 76%)	5% (-96%, 54%)	39% (-26%, 71%)
Sweden	**49% (38%, 58%)**	**67% (60%, 73%)**	**37% (26%, 48%)**	**60% (51%, 67%)**
UK	7% (-14%, 24%)	**40% (28%, 50%)**	-14% (-38%, 6%)	**27% (13%, 39%)**
Overall	**34% (23%, 43%)**	**54% (46%, 60%)**	**21% (11%, 29%)**	**44% (36%, 51%)**

Wet includes snow and ice. Figures in BOLD were statistically significant

The results in Table 3 again show that the estimated reductions in single-vehicle injury crashes from ESC fitment differed considerably across countries and speed zones. This is not surprising as quite different road conditions exist for say Australia compared to Sweden, and as ESC has been shown to be more effective in road conditions that provide less traction for tyres, such as wet/snowy/icy roads, which are more common in Sweden.

ESC and vehicle size and type

Table 4: Combined countries: single vehicle benefits by vehicle size, speed zone, and road condition

Vehicle Size	Speed Zone	Road Condition	Reduction
Small Car	<75km/h	Wet/Snow/Ice	31% (18%-41%)
Small Car	<75km/h	Dry	17% (8%-27%)
Small Car	≥75km/h+	Wet/Snow/Ice	51% (41%-59%)
Small Car	≥75km/h+	Dry	41% (31%-49%)
Large car	<75km/h	Wet/Snow/Ice	37% (24%-48%)
Large car	<75km/h	Dry	25% (11%-36%)
Large car	≥75km/h+	Wet/Snow/Ice	55% (46%-63%)
Large car	≥75km/h+	Dry	46% (36%-55%)
SUV	<75km/h	Wet/Snow/Ice	52% (28%-67%)
SUV	<75km/h	Dry	42% (16%-60%)
SUV	≥75km/h+	Wet/Snow/Ice	66% (49%-77%)
SUV	≥75km/h+	Dry	59% (40%-72%)

The results in Table 4 show that the reduction in single-vehicle injury crashes from ESC fitment was greater on wet, snow and icy road conditions and in higher speed zones. For some of the individual country comparisons (especially Sweden and Italy) there were consistent statistically significant benefits estimated, albeit with wide confident limits. Such a fine disaggregation by vehicle type and road conditions has not been previously reported, and only achievable here from the amount of data included using the prospective meta-analysis approach.

ESC Benefits (Multi-Vehicle Crashes)

Unlike other earlier individual studies, the MUNDS analysis was able to show some marginal benefits also for ESC in multiple vehicle crashes, due to the additional data available, as shown in Table 5.

Table 5: Multi-vehicle crashes benefits speed zone overall and by individual country

Country	<75km/h	≥75km/h
Australia	-7% (-24%, 9%)	6% (-12%, 21%)
Finland	-14% (-72%, 25%)	0% (-53%, 35%)
Italy	9% (-1%, 18%)	**20% (9%, 30%)**
NZ	-11% (-70%, 28%)	3% (-50%, 37%)
Sweden	**20% (12%, 27%)**	**29% (19%, 38%)**
UK	-3% (-13%, 5%)	**9% (0%, 17%)**
Overall	**7% (1%, 12%)**	**14% (6%, 21%)**

Figures in BOLD were statistically significant

There were significant reductions in injury risk from ESC in multi-vehicle crashes by country and speed limit zone. This result, too, has not been previously reported.

MUNDS VALIDATION

The final analysis undertaken here was to compare the results obtained from the MUNDS analysis with similar results previously published.

Crash Type	MUNDS	Farmer (2006)	Lie et al (2006)	Scully & Newstead (2007)	Høye (2011)
All single vehicle crashes	22-26%	33%	17%	27%	32%
All multi-vehicle crashes	7-14%	25%	unk	unk	6%
Crashes in Wet	44%	unk	49-56%	unk	unk
SUV - Single	71%	49%	unk	68%	50%

It is acknowledged that this is not so much a test of validity but more an indication of the worth of the prospective meta-analysis approach. It should also be noted that there were differences in the approaches adopted to control for differences in exposure in different studies. Most studies used an induced exposure method, although others used licensed vehicles or no measures at all. This needs to be taken into account when comparing across studies as it can influence the result obtained.

Of interest, though, these results do show a degree of consistency between the MUNDS findings reported above and those from other published studies. Of particular interest was the finding from Høye (2011) which used a retrospective meta-analysis involving a number of relevant international publications.

The MUNDS findings are generally within the broad range of earlier reported results, for all single vehicle crashes, multi-vehicle crashes and SUVs, albeit towards the top end of magnitude of effects found. The divergences in these findings should not be too surprising. Apart from differences in methods and exposure measures, there are quite different road, speed, and weather conditions across these individual countries as well as differences in the rates of ESC fitment, and motoring cultures more generally. The degree of consistency achieved supports the prospective meta-analysis approach as a useful additional tool for evaluating vehicle safety technologies.

GENERAL DISCUSSION

This study set out to test the value of the prospective meta-analysis approach and to demonstrate the benefits in terms of time saved and additional insights from the approach. The ESC safety technology was chosen for comparison, given the range of previous studies already reported on the benefit of this technology. The results outlined above directly impact on these objectives.

The effectiveness of ESC in reducing injury-related crashes, using the prospective meta-analysis approach involving national police data from 6 countries in Europe and Australasia, was confirmed. While one or two of the individual country analyses were statistically significant, the overall meta-analysis of all databases proved to be both more robust and with less variance. This translates to an ability to produce results in a much shorter timeframe than any one country could achieve by itself, using this approach.

We attempted to clarify the importance of the approach to aggregate data across countries. The main benefit consists of a narrowing of the confidence intervals, which is mainly a function of increased sample size. It is therefore an expected result that some of the MUNDS confidence intervals exclude estimates generated by smaller studies. But it is worth noting that apart from one early result (Becker et al, 2004), the MUNDS estimates and CIs essentially overlap with other reported figures, given the crash type variations.

Furthermore, the prospective approach of combining common aggregate analyses reduces the need for combining individual records in a common database, thereby eliminating difficulties in sharing confidential and private records, but still achieving more timely results of technology effectiveness.

A larger database obtained here not only achieved the benefits in improved timing to report important findings for governments, industry and the community generally, but did reveal some additional insights from the prospective meta-analytic approach.

There are always issues of representation when conducting effectiveness evaluations. Individual countries have their own characteristics which always beg the issue of how general the finding might be internationally. Thus, combining data from several different countries can at least partially if not fully overcome this weakness. Thus, new findings become available that previously known.

The results of this study confirmed many of the benefits of ESC previously reported, albeit of different intensity in many cases. For instance, the effect of vehicle size and type by the road condition at the time across countries with differing weather patterns was better controlled for here. The effects of ESC on single-vehicle crashes were replicated again in this study but so too, were benefits of the technology in multi-vehicle injury crashes which has not always been found presumably because the benefits are smaller, and thus not detectable by smaller sample sizes. The approach enabled multiple comparisons of synergistic effects between the three key independent variables to be modelled and reported. New findings for the effects of crash severity (expressed in terms of different speed zone crashes) were reported here which to the authors' knowledge is a novel finding, not previously quantified.

Validation of the technique

A major objective in this study was to validate the prospective meta-analysis application and ensure that the technique did not provide spurious results. Of course, this could not be done in a precise manner here, given the variations across studies in terms of road design and driving conditions, annual mileage, vehicle fleet mix and driving culture, to mention a few. Nevertheless, it was possible to control for some of the differences between countries by the use of regression modelling to overcome the obvious sources of biases such as driver and vehicle age.

The findings for all single vehicle crashes reported here of between 22 and 26 percent was within the spread of earlier finding by Farmer (2004, 2006), Lie et al (2006) and Scully and Newstead (2007) for similar-aged vehicles and crash periods. The findings for wet roads of 44% was not that different to Lie et al (2006) figure of 49 to 56 percent, especially when considering that Lie's findings were based on Swedish roads where inclement weather is severe. The advantage of ESC in single-vehicle crashes involving Sport Utility Vehicles (SUVs) was much higher than for passenger cars, consistent with those reported by Farmer (2006), and Scully and Newstead (2007). Importantly, there was good consistently with the retrospective met-analysis of ESC by Høye (2011) involving prior reports from similar regions.

It is acknowledged however that the validation process conducted here was hardly a rigorous test of the method's validity. Nevertheless, there were some interesting comparisons found that go some way to sanctioning the approach.

Exposure to risk

One of the important methodological issues in conducting the validation exercise was the choice of an appropriate measure of exposure to control for varying traffic volumes and crash types. As noted in the text, rear-end crashes were used as a measure of overall exposure to risk across all countries in the model and thus the effects of ESC could then be estimated by a reduction in prevalence of other crash types (those presumably affected by ESC) in relation to the prevalence of rear-end crashes (those not affected by ESC).

The induced exposure method has been used in many similar evaluations and the particular procedure used here has been adopted from previous peer-reviewed findings (Tingvall et al, 2003: Page and Cluny, 2006; Lie et al, 2004, 2006; Scully and Newstead, 2007; and Keall and Newstead, 2009). Farmer (2004, 2006) used number of registered vehicles as a measure of exposure, but these figures were not always readily available in the MUNDS countries. Nevertheless, it is argued that induced exposure has many benefits for its use in studies such as this one and that it provides a more rigorous and viable measure of exposure for applications such as this one.

Study limitations

It is acknowledge that the MUNDS study analysis, like all technology evaluations, was not without its limitations. First, there were likely inconsistencies between the databases used in this study. While each contributor used national data, differences in the way and accuracy of data collection across the regions is common. In particular, the way each study reported injuries and their severity likely differed across databases. The Finnish database, for example, only included crashes that resulted in injuries to the driver, which is a source of some heterogeneity. This of course is also a problem for "retrospective" analyses from different studies that also use different databases.

Differences in vehicle fleets and annual mileage were likely across countries, meaning that the findings here might not be representative of any particular country. While this was an important for international representativeness, the results are probably more representative of Europe as a whole than other regions. In addition, the use of speed zone as a proxy for crash severity is not without some criticism. It implicitly assumes that higher speed zones are associated with higher speed crashes, and lower speed zones with lower speed crashes. Newstead *et al* (2010) have used this technique in assessing real-world vehicle crashworthiness with some success. Although such assumptions may not affect analyses of large datasets as were available here, it would be useful if this assumption was able to be tested in future research.

The set of comparison crashes used to provide a measure of exposure to risk has been identified by previous research as one of the better induced exposure measures, although driver age and vehicle type are two factors across which the rear-end crashes provide biased measures of exposure (Keall and Newstead, 2009). However, by including these factors as covariates in our models, we have accounted for at least these sources of bias in forming our estimates.

CONCLUSIONS

This study set out to test the value of the prospective meta-analysis approach and to demonstrate the benefits in terms of time saved and additional insights from the approach. Its hypothesis was that the results of the MUNDS effectiveness analysis (for Electronic Stability Control – ESC) would be consistent with those published earlier. We contend that the results reported here support the validity of the MUNDS approach to estimating technology effectiveness.

Several new findings are reported in the interaction between the independent variables of road condition, speed zone and vehicle size and type in single-vehicle crashes. Given the larger and common database assembled, multi-vehicle crashes also benefited from ESC, albeit of less impact. In addition, the percentage reductions reported for the independent variables of road condition and vehicle size and type were shown to be consistent with previous published findings.

The new methodology developed here using a prospective meta-analysis approach has the advantage of expediting the process of evaluating new vehicle safety technologies. In reality, it is the only feasible approach to study real-world safety benefits when one data source is not sufficient. Drawing from a larger pool of crash data enhances the likelihood of demonstrating statistical significance with tighter confidence bounds. The MUNDS approach will be of potential benefit to vehicle manufacturers and suppliers, governments and consumer groups and advocates in prioritising future road safety improvements in active safety. While a number of limitations were identified with the findings that should be addressed in future research, nevertheless, the MUNDS approach needs to be adopted widely for the benefit of all road users.

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Detection of Driver Impairment from Drowsiness

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ABSTRACT

Drowsy driving is a significant contributor to death and injury crashes on our nation's highways accounting for more than 80000 crashes and 850 fatalities per year. Recent research using data from the 100-car study found that drowsy driving contributed to 22% to 24% of crashes and near-crashes observed. This paper describes an approach that detects impairment from drowsiness in real time using inexpensive vehicle-based sensors to detect drowsiness-related changes in drivers' behavior.

Data were collected on the National Advanced Driving Simulator from 72 volunteer drivers. Three age groups (21-34, 38-51, and 55-68 years of age) drove through representative situations on three types of roadways (urban, freeway, and rural) at three times of day (9 am-1 pm, 10 pm-2 am, and 2 am – 4 am) representing different levels of drowsiness.

Driving data indicated that a complex relationship exists wherein driving performance improves with low levels of drowsiness in the early night session before degrading in the late night session. This study demonstrates the feasibility of detecting drowsiness with vehicle-based

sensors. Results show that alcohol and drowsiness impairment do not allow for a single algorithm to detect both types of impairment; however a single algorithm approach with different training data for the different types of impairment may be successful. To detect impairment due to either alcohol or drowsiness, a more complex approach is necessary where separate algorithms are combined to work with each other. These results suggest promise in a vehicle-based approach to detecting and differentiating multiple types of impairment.

INTRODUCTION

Exact counts of the number of crashes caused by drowsiness are hard to obtain due to the use of varying methodologies. The Gallup organization surveyed drivers and estimated that during the 5 years prior to 2002 and found that 1.35 million drivers may have been involved in a drowsy driving related crash [1]. A National Highway Traffic Safety Administration (NHTSA) report, which contained crash report data between 2005 and 2009, attributed 83,000 crashes per year and 886 fatal crashes per year to drowsy, fatigued, or sleeping drivers. Over the five-year period these causes resulted in 5,021 fatalities.

Other research methods and driver populations lead to different estimates for the percentage of drowsy driving crashes. The 100-car naturalistic driving study found that drowsy driving contributed to 22% to 24% of crashes and near-crashes observed [2]. In a report to congress, NHTSA stated that 3.2 % of crashes were related to actual sleep [3]. An estimated 1% of all large-truck crashes, 3–6 % of fatal heavy-truck crashes, and 15–33% of fatal-to-the-truck-occupant-only crashes have been attributed to driver fatigue as a primary factor [4]. Although the methodologies result in different estimates, all point to a significant problem.

According to the National Sleep Foundation's 2009 annual Sleep in America survey, 28 percent of drivers had driven while drowsy at least once per month in the past year. Of those that drove while drowsy, 28% have fallen asleep [5]. A survey conducted in 2003 found that 37% of drivers have fallen asleep for at least a moment (nodded off) while driving at least once in their driving career, while 8% of them had done it in the last six months.

Of those encountering a sleeping episode, 58% of drivers were on a multi-lane interstate highway, and 92% of them were startled awake and of those who were startled awake, 33% wandered into another lane or shoulder, 19% crossed the centerline and 10% ran off road [1]. Drowsy driving is not only common in the United States, it was found that one in five Canadian drivers have admitted to nodding off or falling asleep at least once while driving [6] and that driver fatigue contributes to at least 9% to 10% of crashes in the UK [7].

Clearly, there is cause for concern about the rate of drowsy driving and the resultant crashes, injuries and fatalities. This concern creates a need for research to facilitate the development of technological approaches that will reduce the number of lives lost due to drowsy driving. The present aim is to extend Impairment Monitoring to Promote Avoidance of Crashes using Technology or IMPACT, a program of research into detecting alcohol-impaired driving based primarily upon vehicle-based measures to the domain of drowsy driving [8]. IMPACT has developed alcohol detection algorithms for all drivers (general algorithms) and algorithms that take into account individual driving differences (individualized algorithms). This work explores how well the previously developed algorithms that detect impairment from alcohol are able to detect drowsiness, and how best to modify those algorithms, if necessary, to detect both. The algorithms that were previously developed to detect alcohol impairment were effective at levels comparable to the Standardized Field Sobriety Test in eight to twenty-five minutes.

Although there were many objectives to this research, this paper will focus on the following:

- Can existing algorithms for detecting impairment be used to detect drowsiness?
- Can real-time algorithms reliably detect drowsiness in advance of a drowsiness-related mishap?

METHOD

Participants

Data were collected from 72 volunteer drivers from three age groups (21-34, 38-51, and 55-68 years of age) driving through representative situations on three types of roadways (urban, freeway, and rural). Participants drove at three times of day (9 am-1 pm, 10 pm-2 am, and 2 am – 4 am) to induce different levels of drowsiness.

To be eligible, participants were required to:

- Possess a valid US driver's license
- Have been licensed driver for two or more years
- Drive at least 10,000 miles per year
- Have no restrictions on driver's license except for vision
- Not require the use of any special equipment to drive.

Procedure

An initial telephone interview was conducted to determine eligibility for the study. Applicants were screened in terms of health history, current health status, medication and drug usage, morning/evening tendencies [9], and sleep apnea history [10]. Pregnancy, disease, or evidence of sleep apnea or being a night person were excluded from the study as were those taking prescription medications that cause drowsiness.

Each participant participated in four sessions over three visits. The two overnight drives occurred on a single night. The daytime and nighttime data collection visits were separated by three days and the order of these visits and scenario event sequence were counterbalanced

On study Visit 1 (screening), each participant informed consent was obtained. They then provided a urine sample for the drug screen and, for females, the pregnancy screen. During a five-minute period following these activities, the participant sat alone in the room where subsequent measurements of blood pressure, heart rate, height, and weight were made.

Cardiovascular measures were taken and compared to acceptable ranges (systolic blood pressure = 120 ± 30 mmHg, diastolic blood pressure = 80 ± 20 mmHg, heart rate = 70 ± 20) to assess eligibility for the study. If participants met study criteria, they completed demographic surveys. These surveys included questions related to crashes, moving violations, driver behavior, sleeping, and driving history. Participants viewed an orientation and training presentation that provided an overview of the simulator cab and the secondary task they were asked to complete while driving.

The task consisted of the participant turning on the CD player and sequentially advancing the CD player to two tracks provided in an auditory cue and then turning off the CD player.

Participants then completed the practice drive and completed surveys after their drive about how they felt and about the realism of the simulator. The practice drive included making a left hand turn, driving on two- and four-lane roads, and changing CDs. If the participant remained eligible, baseline EEG measurements were recorded. Prior to their study visits, participants were provided with activity monitors and activity logs to verify sleep preceding the visits.

During the daytime-alert visit, participants were asked to not ingest any caffeine. Logs were reviewed to verify a normal night's sleep (at least six hours) the preceding night. Their BAC was checked to ensure that they were not under the influence of alcohol. Participants were then fitted with the wireless B-Alert X-10 EEG cap [11], [12] and electrodes to record their EEG and heart rate. The participants then entered the simulator and eye tracking calibrations were completed.

Prior to beginning the drive, the participants also completed a questionnaire about their current sleepiness level, the Stanford Sleepiness Scale [13], and a version of the Psychomotor Vigilance Task or PVT (Cognitive Media Iowa City, IA) based on the Psychomotor Vigilance Task [14], [15]. The participants drove through the simulation scenario.

Following the drive, participants were again administered the Stanford Sleepiness Scale, the wellness survey, PVT, a Retrospective Sleepiness Scale, and a simulator realism survey. The Retrospective Sleepiness Scale required subjective judgments of drowsiness at specified scenario locations. The B-Alert cap was then removed.

During the nighttime-drowsy visit, participants were instructed to restrict beverage consumption to water after 12:00 pm on the day of their overnight visit, to minimize caffeine intake. Participants were picked up at their homes after having eaten dinner, and transported to the simulation facility to arrive around 7pm. Logs were reviewed to verify a normal night's sleep (at least six hours) the preceding night and that they did not take any naps during the day. Caffeine intake was reviewed and if caffeine was consumed after noon on the day of the overnight drive, the participant was either rescheduled or dropped from the study. Participants were then fitted with the B-Alert monitoring device.

A variety of activities were provided to keep participants awake including activities on an iPad, reading, playing computer games, etc. They were monitored to ensure they did not fall asleep or converse with other participants. If participants began to fall asleep, they were engaged by a researcher to keep them awake. The participants completed the Stanford Sleepiness Scale every 30 minutes until they drove. One hour prior to their drive, they were taken to a private room to wait. They completed a PVT at this time, and also at 30 minutes prior to the drive. Participants were escorted to the simulator between 22:00 and 01:00 for their first drives. Once in the simulator, eye tracking calibration procedures were performed, and the B-Alert electrode connection was verified. Before starting the drive, the participants completed a PVT and Stanford Sleepiness Scale. After the drive, participants completed the Stanford Sleepiness Scale, a Wellness Survey, a PVT, and a Retrospective Sleepiness Scale.

Participants were then escorted back to a separate waiting area where TV, movies, reading, computer games, etc. were available. A Stanford Sleepiness scale was administered every 30 minutes until their next drive. One hour prior to their second drive times, participants were again taken to a private room to wait. They completed a PVT one hour prior to the drive and also at 30 minutes prior to the drive. Participants were escorted to the simulator between 02:00 and 05:00 for their second drives. Once in the simulator, eye tracking calibration procedures were performed, and the B-Alert connection was verified. Before starting the drive, the participants completed a PVT and Stanford Sleepiness Scale. After the drive, participants completed Stanford Sleepiness Scale, a Wellness Survey, a PVT, a retrospective sleepiness scale, and a realism survey. The B-Alert system was then removed and they were transported home

Apparatus

The National Advanced Driving Simulator (NADS), shown in Figure 1, made it possible to collect representative driving behavior data from drowsy drivers in a safe and controlled manner. This is the highest fidelity simulator in the United States and allowed for precise characterization of driver response. Drivers' control inputs, vehicle state, driving context, and driver state were captured in representative driving situations (see Figure 2).

Simulator Scenario

Each drive was composed of three nighttime driving segments. The drives started with an urban segment composed of a two-lane roadway through a city with posted speed limits of 25 to 45 mph (see Figure 3 and Figure 4) with signal-controlled and uncontrolled intersections. An interstate segment followed that consisted of a four-lane divided expressway with a posted speed limit of 70 mph. Following a period in which drivers followed the vehicle ahead, they encountered infrequent lane changes associated with the need to pass several slower-moving trucks (see Figure 5). The drives concluded with a rural segment that was composed of a two-lane undivided road with curves (see Figure 6); followed by a gravel road segment; and then a 10-minute section of straight rural driving.

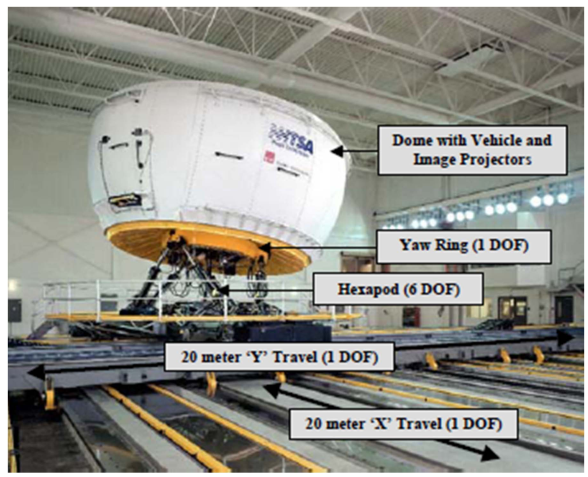

Figure 1. The NADS-1 high-fidelity driving simulator.

Figure 2. An urban driving scene from the NADS-1 simulator.

Figure 3. Approach to curve in urban drive

Figure 4. Straight roadway segment in urban drive

Figure 5. Passing truck on Interstate.

Figure 6. Approach to rural curve

RESULTS

Sensitivity of Scenarios to Drowsiness

An analysis of common driving metrics of variability in speed and lane keeping demonstrates the sensitivity of the NADS-1 to drowsiness. Driving data indicated that a complex relationship exists wherein driving performance improves with low levels of drowsiness in the early night session before degrading in the late night session (see Figure 7). Session time of day did not interact with age, gender, or roadway situation.

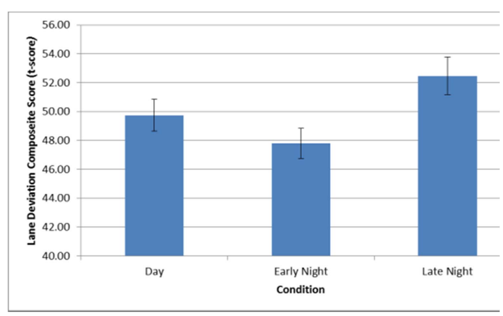

Figure 7. Lane deviation scores by Drowsiness Condition

Detecting Impairment from Drowsiness

The primary objectives for algorithm development and evaluation include:

- Evaluate existing algorithms for detecting impairment for detection of drowsiness
- Determine if real-time algorithms can reliably detect drowsiness in advance of a drowsiness-related mishap

An initial set of algorithms was selected for evaluation based on prior studies in this line of research and a review of the literature. For those selected from the open literature, only those algorithms with enough detail for real-time implantation were considered. The algorithms used in the evaluation are documented in Table 1.

Table 1. Summary of Algorithms

Label	Algorithm	Inputs	Outputs
PC	PERCLOS [16]	Eye closure	Continuous percentage Drowsy binary
PC+	PERCLOS+ [17]	Eye closure, lane departure	Drowsy categorical (low, moderate, severe)
SB	Steering-based [18]	Steering angle, steering rate	Drowsy binary
EEG	EEG [19]	Scalp electrical activity	Continuous probability Drowsy binary
DT	Decision Tree[8]	Multiple measures of driver performance	Intoxicated binary
MDD	Multi-Distraction Detection [20]	Eye gaze location	Continuous PRC Visual binary Cognitive binary
TLC	Time-to-lane-crossing[19]	Lane position, lane heading angle	Drowsy binary
SRF	Steering random forest [19]	Steering wheel angle	Drowsy binary
BN	Bayes Net [19]	Multiple measures of driver performance, eye closure, eye closure rate	Intoxicated categorical (none, moderate, severe)

Table 2 shows algorithm performance in detecting drowsiness, as defined by drivers' ratings of sleepiness using the SSS after they completed the drive. Drowsiness was indicated by post SSS of five or greater and alertness by post SSS of three or less. In this table, the algorithms were assessed according to how well they differentiated between drivers with a rated sleepiness score of three or less and those with a score of five or greater.

Three standard criteria were used to assess algorithm performance in detecting and distinguishing impairments: accuracy, positive predictive performance (PPP), and area under curve (AUC). Accuracy measures the percent of cases that were correctly classified, while PPP measures the degree to which those drivers that were judged to be drowsy were actually drowsy. An algorithm can correctly identify all instances of impairment simply by setting a very low decision criterion, but such an algorithm would misclassify all cases where there was no impairment. The relationship between the true positive detection rate (sensitivity) and false positive detection rate (1-specificity) is represented by the receiver operator characteristic (ROC) curve. AUC represents the area under the receiver operator curve, which provides a robust and simple performance measure. Perfect classification performance is indicated by an AUC of 1.0, and chance performance is indicated by .50. AUC is an unbiased measure of algorithm performance, but accuracy and PPP are more easily interpreted, so all three are used in describing the algorithms.

Surprisingly, all algorithms performed poorly with only the PERCLOS algorithm having a confidence interval that did not include.50. The mean AUC for the PERCLOS algorithm was only.61, meaning that if the driver was drowsy the algorithm would only have a 61% chance of correctly detecting the drowsiness.

Table 2 Impairment detection algorithm performance based on post-drive sleepiness ratings with 95% confidence intervals

Label	Algorithm	AUC	PPP	Accuracy
MDD	Multi-Distraction Detection	.51 (.45-.61)	.59 (.55-.62)	.55 (.53-.55)
EEG	EEG	.58 (.48-.65)	.54 (.53-.55)	.59 (.56-.61)
PC	Perclos	.63 (.53-.70)	.60 (.59-.60)	.59 (.55-.61)
PC+	Perclos+	.53 (.43-.60)	.59 (.58-.60)	.54 (.53-.59)
SB	Steering-based	.55 (.48-.62)	.59 (.58-.59)	.56 (.54-.59)
BN	Bayes Network	.45 (.38-.57)	.48 (.45-.51)	.49 (.47-.51)

The algorithm developed to detect distraction (MDD) performed very poorly, comparable to a random classifier. Similarly, the Bayes Network trained to detect alcohol impairment also performed very poorly, and algorithms developed to detect drowsiness performed almost as poorly. Overall, these results show that algorithms developed to detect other impairments will not necessarily detect overall drowsiness as determined by SSS rating.

In switching to the second objective, it is not surprising that algorithms detecting impairment defined by the drowsiness condition performed poorly when the variability of drowsiness across conditions, drivers, and the drive are considered. The transient nature of drowsiness suggests that algorithms that detect impairment associated with driving mishaps, such as lane departures, might be substantially more sensitive.

To assess this possibility, real-time algorithms were developed using data from a small time window, with a focus on data surrounding lane departures. The continuous data consists of driver and vehicle data recorded at 60 Hz for the entire drive. Each record of these datasets was coded as alert or drowsy according to three definitions: the drowsiness condition (Day, Early Night, Late Night), a linear combination of PVT, pre-post and retrospective SSS, and the presence or absence of a lane departure.

Ten-fold cross validation was used to assess each algorithm, producing a measure of accuracy, PPP, AUC, timeliness and corresponding confidence interval for each algorithm. Timeliness is defined by the AUC of the ROC curve measured at six seconds before the lane departure. ROC curves summarize the performance graphically.

Data mining algorithms (Bayesian Networks and Random Forest), designed to detect and classify drowsiness in real time, successfully detected drowsiness six seconds before it resulted in a lane departure (see Figure 8and Figure 9. These algorithms were based on time-to-lane-crossing (TLC) and steering behavior using sensor data already available in cars. They performed better than PERcentage of CLOSure of the eyelid (PERCLOS), see Figure 10, which uses eye-tracking cameras that are not currently available in the vehicle fleet. We have demonstrated that inexpensive vehicle-based sensors can be used to successfully detect driver impairment

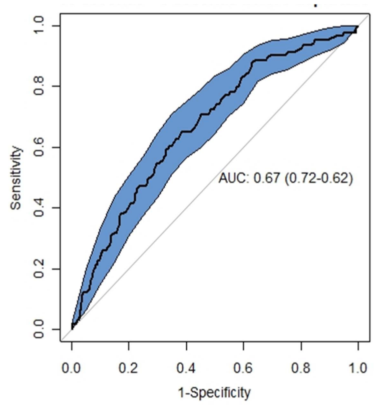

Figure 8. Receiver operator characteristic of steering

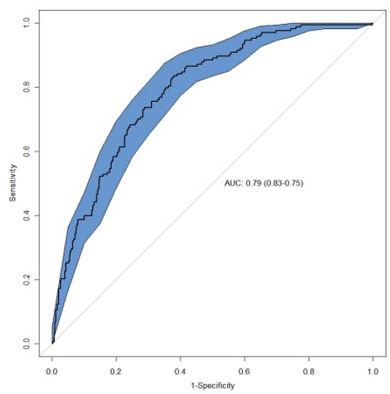

Figure 9. Receiver operator characteristic of TLC algorithm

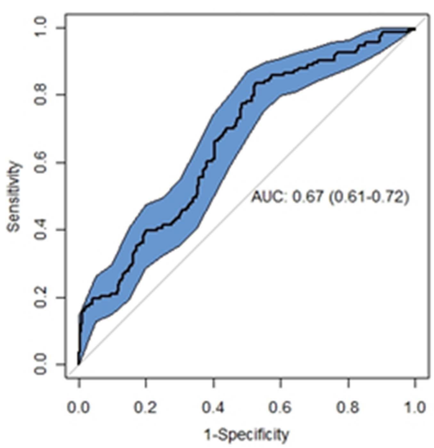

Figure 10. Receiver operator characteristic of PERCLOS algorithm

It was found that such algorithms could be generalized to detect both alcohol impairment and drowsiness with additional training or by combining multiple algorithms. However, algorithms that were trained to detect alcohol impairment did not perform well when simply applied to drowsiness and vice versa.

Drowsiness has a strong transient component, as compared with intoxication which is longer-lasting. In fact a Bayes Net was able to differentiate intoxication from the combination of intoxication and drowsiness, showing that the symptoms of the former do not necessarily mask those of drowsiness.

CONCLUSIONS

This study demonstrates the feasibility of detecting drowsiness with vehicle-based sensors. Results show that the differences in alcohol and drowsiness impairment do not allow for a single algorithm to detect both types of impairment; however similar algorithms trained independently may be successful. To detect impairment due to either alcohol or drowsiness, a more complex approach is necessary where separate algorithms are combined to work with each other. These results suggest promise in a vehicle-based approach to impairment detection including multiple types of impairment.

Future research should focus on examining distraction related impairment to evaluate the extent to which distraction can be detected when drivers are impaired from alcohol or drowsiness, and the extent to which impairment from alcohol, drowsiness and distraction can be distinguished. Then other types of impairments may also be considered, such as drugs and age-related cognitive decline.

Additional research should evaluate the extent to which existing impairment detection algorithms are capable of detecting impairment from medications or illicit drugs. Many over the counter medications are known to produce drowsiness; however, because these medications produce a more uniform level of drowsiness compared to the transient nature of the natural onset of drowsiness, this type of impairment should be tested to determine if the algorithms developed to detect drowsiness as part of this research would detect driving impaired by medications or illicit drugs.

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VERIFICATION OF PROPOSED DRIVER ALCOHOL DETECTION METHODOLOGY OF ELECTRODERMAL ACTIVITY USING ELECTROENCEPHALOGRAMS AND PATCH TESTS

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ABSTRACT

This paper describes the verification of alcohol detection methodology that measures changes in electrodermal activity (EDA) using electroencephalograms and conductive patch tests. We tested the methodology using a direct current potential method. First, it was revealed that the direct current potential method could detect alcohol in 70% of human subjects by analyzing absolute values of data waves or through a post-processing method. Second, mice that do not sweat were tested to observe the changes in EDA values before and after they were injected with alcohol because EDA might be affected by sweat in humans. Third, to clarify the local mechanism of EDA, fluctuations in ion concentration distribution were analyzed using artificial cells. The results indicate that EDA changed significantly before and after drinking alcohol, with no effects from sweat; EDA could be measured before and after alcohol intake; and EDA data were available for human skin covered with durable materials. Changes in EDA have been considered to be caused by differences in ion concentrations during transport across the cell membrane, but our experiments using artificial cells revealed that ion concentration was not changed locally by alcohol concentration. It is concluded that drinking alcohol does not cause changes in alcohol concentration by ion transport in the local cell membrane, but has some effect on the transmission system between human cells. However, this requires consideration of alcohol resistance in the human body.

This study clarifies the transmission system between human cells by measuring changes in electroencephalograms before and after drinking alcohol using an electroencephalograph (EEG), and verifies the relationship between EDA and the presence or absence of alcohol resistance by performing a patch test. Changes were observed in the frequency of EEGs before and after drinking alcohol, which suggests that changes in EEGs would have some effect on the transmission system between human cells and cause changes in EDA. In addition, considering the relationship between the patch test and EDA, differences in EDA were small in cases where volunteers were likely to have alcohol resistance, while they were large in cases where volunteers were likely to have no alcohol resistance. Further studies are expected to develop effective driver alcohol detection systems with cost advantages.

INTRODUCTION

Traffic accidents caused by drinking and driving occur around the world, leading to large social and damage costs. Legislation to ban drink-driving is implemented on a mandatory basis in some countries but not in others. In Japan, traffic accidents involving drivers drinking alcohol are often reported, even though drink-driving is restricted. Drivers are sometimes checked by breath alcohol equipment and violent drivers may be arrested, but traffic accidents have never been reduced to zero.

Meanwhile, in the United States, a research partnership between the National Highway Traffic Safety Administration (NHTSA) and motor vehicle manufacturers is attempting to develop a driver alcohol detection system[1)]. Their research and development comprises two approaches, and the results from Phase I were reported at the Enhanced Safety of Vehicles (ESV) conference in 2011. One approach was a method to measure alcohol concentrations in drivers' breath from the ambient air in the vehicle cabin. The other was a direct method to precisely measure blood alcohol concentrations within the first few millimeters of drivers' finger tissues. It may be presumed that the measuring instrumentation and installation would be expensive in both cases.

We have performed fundamental studies in an effort to develop a direct alcohol measurement system as an alternative to the current, simple breath-based measurement system. Our direct method potentially has similar performance to the breath-based system, but it also takes into account the duration of the influence of alcohol and is more widely applicable.

RESULTS ACCOMPLISHED BY THE AUTHORS[2), 3)]

The results from studies by the authors are summarized as follows.

Electrodermal activity (EDA)

When humans drink alcohol, ion movements inside and outside cells cause a variation in EDA. If values of the action potential are below a particular threshold, repeated polarization occurs through ion movement inside and outside cells and the measured values of EDA will fluctuate. When the value of the action potential is above the threshold, the value of the electrical potential becomes steady and the EDA becomes comparatively steady. In most cases, the electrical potential difference caused by an action potential is above a threshold in an active phase. Measurement methods exist for inside of cells (endosomatic) and outside of cells (exosomatic). Direct current and alternating current measuring methods are available for exosomatic. Table 1 provides representative measuring methods[4)]. The contact method may apply a weak alternating current, which is used, for example, in lie detection equipment. Alternatively, a contact method can use a direct current that measures differences in electrical potentials between two electrodes, a reference electrode and a measuring electrode, to measure EDA. In this study, the contact method using direct current was applied.

Table 1 Electrodermal activity measurement methods[4)]

Recording	Endosomatic	Exosomatic	
Action current	-	A direct current*	An alternating current
Units	Skin potential	Skin resistance, Skin conductivity	Skin impedance, Skin admittance

* used by the authors

Membrane potential[4)]

When action potentials created by differences in potentials are below the threshold, the following formula can be applied:

$$V_x = V_0 e^{-x/\lambda} \quad (1)$$

Here, V_0 is the signal size at an original point,

V_x is the signal size at a distance, and

λ is a constant of length.

Because the phenomena are modeled exponentially and are repeated, they take the form of a vibrating system with decay. Meanwhile, it is known that an action potential becomes stable when it is above the threshold. Thus, the effect on electric potential by action potentials is transmitted along the axis of a cylinder. This condition can be identified from the results in the experiments.

To clarify the mechanism of internal or external ion flows near the cell membrane, the distribution of ion concentration was observed by an ion probe and a fluorescence microscope before and after alcohol intake, as described below. The results indicate that fluctuations in EDA caused by drinking alcohol could be concluded to occur through action potentials transmitted along an axial cylinder from the brain, because there was no observable change in the ion concentration distribution in artificial cells. Note that this is a result obtained using artificial cells.

Measurement system[4)]

Generally, a measurement system uses a survey electrode placed on the palm, which has many sweat glands, and a reference electrode is placed on the forearm, which has fewer sweat glands. Previous measuring systems consisted of electrodes placed on the forearm and palm, an amplifier, instruments for measuring differences in potentials and a computer for built-in data processing. Figure 1 shows a schematic for such a measurement system.

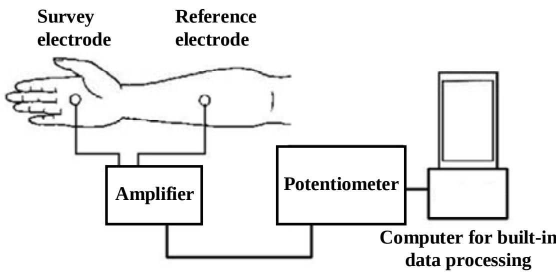

Fig. 1 Schematic of a Measurement System

The types and positions of the two electrodes are typically arranged for specific purposes, as described in the following.

Type of electrodes[4)]

Various types of electrodes exist. In this study, commercially available Vitrode Bs Ag/AgCl paste with a Cotton Tape Disposable Electrode for ECG Monitoring (Nihon Kohden Corporation) was used. This ECG electrode is on the market as a cardiac electrogram monitor and is in general use. The electrode plays the role of a transducer to transform ionic current into an electron current.

Position of electrodes, distance between electrodes, and how to hold the steering wheel[2)]

Although normal practice is to locate the electrodes on the palm and forearm, when starting an engine before driving a vehicle, the driver often pinches an ignition key between the fingers and holds the steering wheel with the palm and fingers. Therefore, experiments were conducted focusing on the positions of the electrodes and the distance between them. First, electrodes were placed on the center of the palm as a reference electrode and on the forearm for measurement. Second, assuming the normal situation for holding the steering wheel, the EDA was measured by electrodes placed on the palm and each of the five fingers. Third, assuming the driver holds an ignition key, the electrodes were placed on the thumb and forefinger. The results measured using the steering wheel and ignition key electrode placements tended to be similar to the palm and forearm placement, confirming that EDA could be measured by electrodes placed with a certain distance between them.

In addition, the configuration of fingers holding a pole was investigated to be sure that the EDA could be measured on a steering wheel. Variations of the orientation of holding were investigated using a straight round bar, with infinite curvature, and a round bar with finite curvature. The result showed that both orientations were similar. In other words, the orientation of the fingers was not affected significantly by the shape of the object being held.

Overall, the two cases of electrode placements for inserting an ignition key and placing the hands on the steering wheel produced similar EDA measurements.

EDA of mice before and after alcohol injection[3)]

An experiment was performed to investigate the EDA of mice that had alcohol injected into their bodies, using the measurement equipment described above with disposable electrodes. Mice do not sweat from their forepaws or hind paws but electrodes placed on the foreleg and hind leg using modified tweezers were found to be effective for obtaining stability data. Figure 2 shows the fluctuations in EDA with time when mice ingested 0.2 cc alcohol solution containing 60% ethanol for mice that were intoxicated, in a coma, or dead. The value of the electrode signal remained stable prior to alcohol intake, but fluctuated after alcohol intake and finally reached zero. Mice that did not sweat at their extremities were used to avoid the effects of sweat, which are known to affect EDA values. The results show that EDA in mice with no sweating effects differed greatly before and after alcohol intake.

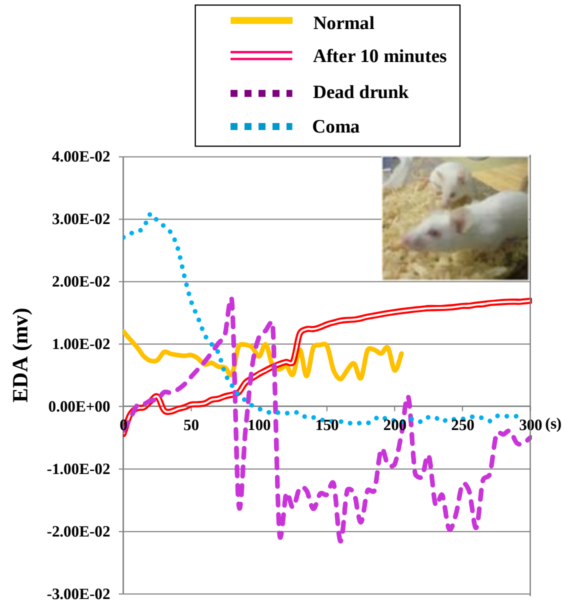

Fig. 2 Relation between EDA and time before and after alcohol intake using mice[3)]

Comparison with the breath alcohol concentration detector system

Values from two types of breath-based measurement system available on the market were compared with the EDA method. The first breath-based system was a blowing type (Urban system CA20000, 1 mg/l) and the second type used breathing into a nozzle (SOCIAC-X , 05 mg/l). Table 2 shows the experimental conditions. Measurements were carried out not only of breath alcohol concentration but also of EDA simultaneously. As a simple countermeasure to the direct influence of sweat, electrodes wrapped with thin plastic wrap were used to measure the EDA. The results are shown in Figure 3. The results confirmed that this simple method was effective for measuring EDA.

Table 2 Experimental conditions

Test No.	Experimental conditions	
1	Before drinking	
	Drinking: 350 ml with 5% alcohol x two bottles	
2	After drinking the first bottle	In 2 minutes after 1 minute passed, the EDA was measured then the breath alcohol concentration was measured.
3	After drinking the second bottle	In 2 minutes after 1 minute passed, the EDA was measured then the breath alcohol concentration was measured.
4	After 12 minutes passed after drinking the second bottle	

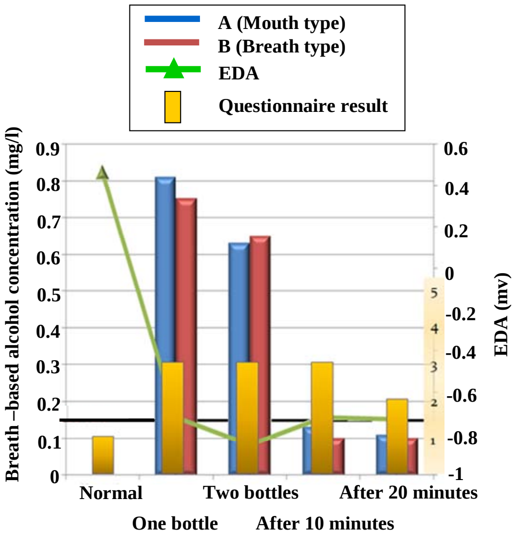

Fig. 3 EDA and Breath-based alcohol concentration as a function of time using human participants[3)]

Comparison with other data

A comparison between breath-based alcohol concentrations and EDA is shown in Figure 4. The breath-based measurement systems provide high values immediately after drinking, but the values drop rapidly and return to normal levels. On the other hand, although the EDA measurement depended on alcohol concentration, it took 8 hours for values to return to normal levels. This was verified by questionnaires to participants. Thus, breath-based measurement systems may sometimes not provide values that match feelings of intoxication.

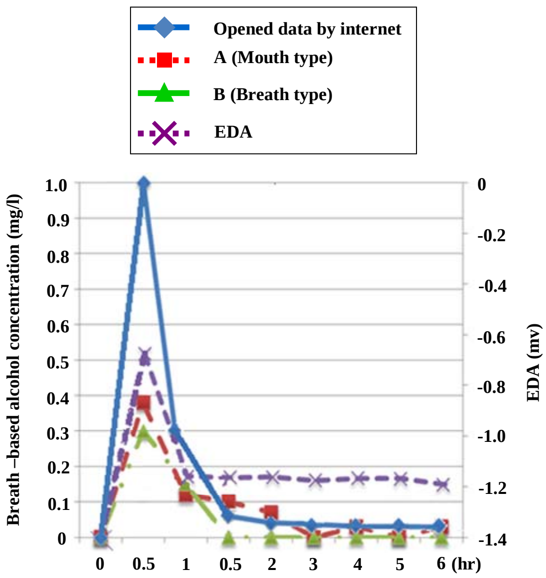

Fig. 4 Comparison between the breath-based alcohol concentration and EDA detection methods with time using human participants[3)]

Artificial cell membrane and fluorescent ion probe experiments

Using an ion probe (Fura 2) that can detect many ions involved in the transmission of information in cells, artificial cells (mouse epidermal keratinocyte lines Pam 212) were observed before and after alcohol intake. The epi-illumination fluorescence microscope was used for observation. Ca was ingested by the ion probe and there was no change seen in the distribution of Ca uptake by the ion probe before and after alcohol intake.

Data processing

It was revealed by absolute level, amplitude, wavelength, tilt, and the filtering process of waves, along with analyses before and after drinking, that drinking alcohol could be detected in 70% of participants[3)].

To clarify the local mechanism of EDA, the Ca ion concentration was analyzed using artificial cells and fluorescence microscopy. As a result, no local or distinguishing changes were observed. It is concluded that EDA fluctuations are not caused by a change in ion concentration in the local cell membrane. That is, we speculate that after drinking alcohol, a human body suffers effects not from changes in ion concentration in the local and terminal cell membrane but from time differences in commands and transmittance from brain cells.

INVESTIGATION OF PRESENT STUDY

To clarify the commands and transmittance from brain cells, measurement of electroencephalograms were investigated before and after drinking. In addition, simple patch tests were conducted for participants to examine alcohol tolerance, making it possible to distinguish between persons with high and low tolerances for alcohol by investigating the correlation between electroencephalograms and EDA. The results show that there were differences between alpha and theta waves, and that participants had two overall tendencies, despite individual variations.

Method

EDA, electroencephalogram and patch tests were performed.

Disposable electrodes were used to measure EDA, along with a simple device for measuring electroencephalograms. The reference electrode was placed on the ear lobe and the sensor band placed on the forehead.

An electroencephalograph (EEG: FM-717) with dedicated software Pullax II was used. Table 3 shows the relationship between available waves and frequency, and the features of each wave.

Table 3 Specifications of electroencephalograph and conditions

Name	Frequency (Hz)	Conditions in a human body
θ	4~7	Often detected in REM sleep
α1	7~9	Feeling drowsy, almost falling asleep
α2	9~11	Relax, high degree of concentration
α3	11~13	Low degree of concentration, calm down
β	13~30	Detected by electroencephalograms in normal conditions

The results in patch tests depend on the amounts of enzyme broken down by the acetaldehyde produced when alcohol is degraded. The determination is shown in Table 4. Rubbing alcohol with 50% isopropanol as a reagent solution, adhesive plasters, and medical gauzes were used.

Table 4 Results and determinations in patch tests

No difference on the skin	→ ALDH2 activate form
Getting red on the skin	→ ALDH2 Low active form

The volunteers were 14 people in total, comprising females and males in their 20s to 30s. Beforehand, they have been provided explanations with materials describing the purpose and nature of the experiments and they then agreed to participate.

Results

EDA

Representative results are shown in Figures 5 and 6. The results show that the wave patterns of EDA after drinking alcohol can change enormously or only slightly, similar to results in previous experiments.

Results from the electroencephalograph

The chart indicates the ratio of electroencephalograms after drinking alcohol for an electroencephalogram in which each frequency level in the normal condition is given the value of one.

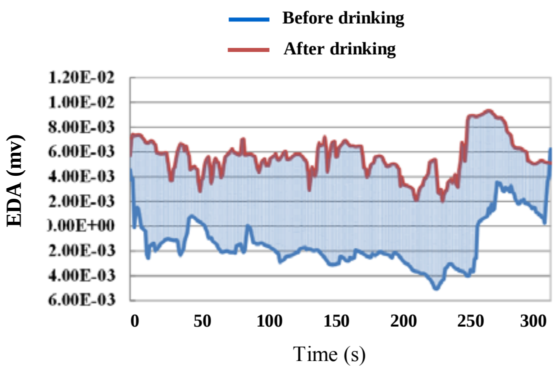

Fig. 5 Changes in EDA after drinking alcohol (example 1)

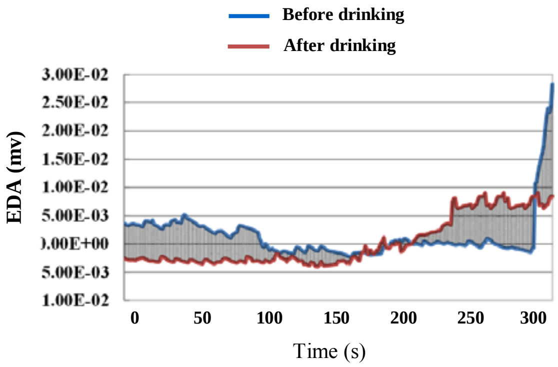

Fig. 6 Changes in EDA after drinking alcohol (example 2)

Three representative examples of results from the electroencephalograph are shown in Figures 7–9. Figure 7 indicates low frequencies increase compared with normal conditions (hereafter referred to as type A). Figure 8 indicates that high-frequency bands increase compared with normal conditions (referred to as type B). Figure 9 indicates that values change randomly compared with normal conditions (referred to as type C).

In any case, changes in the electroencephalograms after drinking alcohol could be measured, from which it can be concluded that alcohol affects the electroencephalograms. Additionally, questionnaires were completed by participants. Participants who answered "feeling sleepy" are often categorized to follow the data in Figure 7 (low frequencies increase: type A), while participants who answered "feeling cheerful or joyful" often belong to Figure 8 (high-frequency bands increase: type B).

Therefore, the results of electroencephalograms corresponded approximately to the results of the questionnaires. Thus, electroencephalograms biased toward low frequencies were associated with feeling sleepy, but conversely those biased toward high frequencies were associated with feeling cheerful.

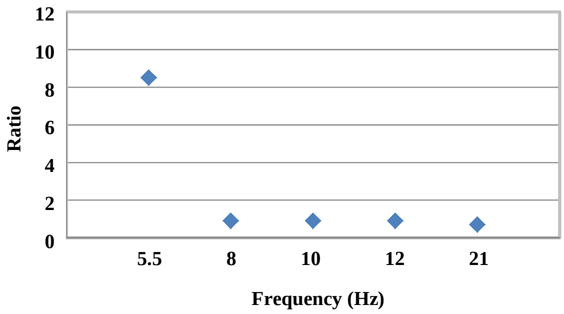

Fig. 7 Results from the electroencephalograph: low-frequency bands get higher (type A)

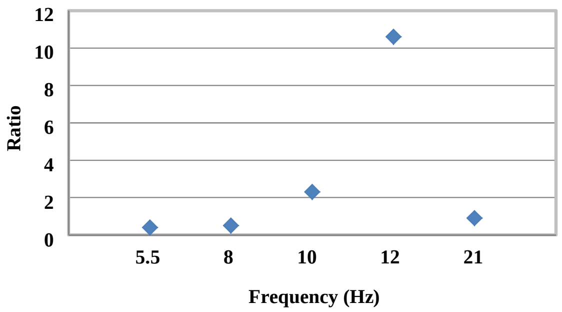

Fig. 8 Results from the electroencephalograph: high-frequency bands get higher (type B)

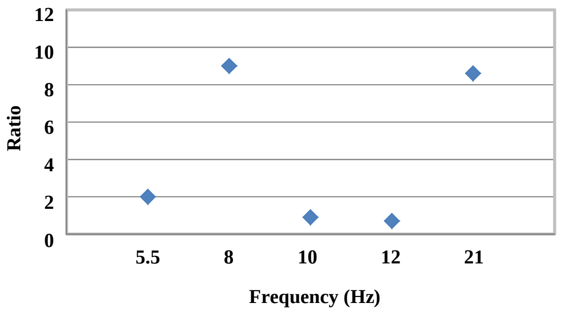

Fig. 9 Results from the electroencephalograph; there is no discernible trend (type C)

Results in patch tests

Proceeding in accordance with the patch tests, Table 5 shows a summary of the results from the patch tests. The results can be classified approximately into two groups, in which changes are shown in some persons but not in others.

Table 5 Summary of results in the patch test

Skin color	Human subjects	Numbers
No change	Having alcohol resistance	6/14
Turning red extremely	Having no alcohol resistance	8/14

Additional experiments

With the objective of putting this method into practical use in mind, additional experiments were performed. When electrodes are placed on an ignition key, any obstacle between the ignition key and the fingers may interfere with the measurement. Therefore, this experiment was conducted by supposing that obstacles with thickness might be inserted between the electrodes. Several materials of different thickness were tested. The results are shown in Figure 10. Papers with thickness equal to or less than approximately 0.8 mm could be measured as Figure 10 shows. However, there were considerable differences between 0.08 and 0.3 mm, and this requires further experiments.

This experiment was also conducted under the condition of wrapping of electrodes, providing further results for samples involving the effects of sweat on electrodes. From a different point of view, electrodes acted as a transducer, in that they converted ion-exchange phenomena to electron-exchange phenomena, a result that changes the role of the electrode. However, this degree of accuracy was not required here.

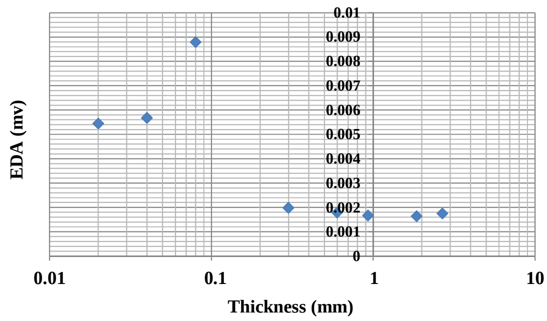

Fig. 10 Changes in EDA by insertion of obstacles

Electroencephalograms can be divided into three types on the basis of clear differences in the results before and after drinking alcohol, as indicated in the electroencephalogram measurements. It was clarified that the first case of a small change in low-frequency content indicated a feeling of sleepiness; the second case associated changes in high-frequency content with a feeling of cheerfulness; and in the third case,

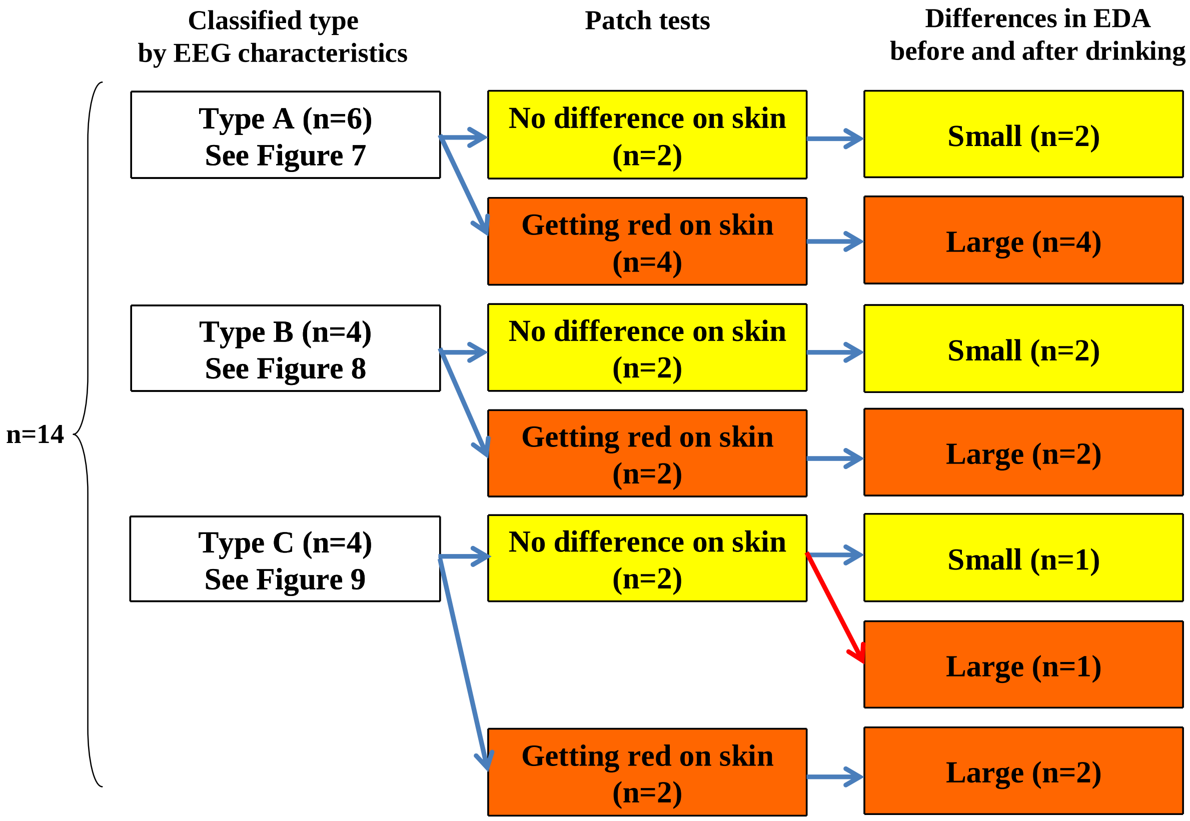

Fig. 11 Correlative relationship of EDA arranged based on the results from the patch test

both the above cases were mixed. Differences in the changes to EDA corresponding to the three types of electroencephalograms were not validated in this experiment.

In addition, the results from the above experiments for EDA were arranged based on the patch tests. Figure 11 shows results classified by the presence (getting red on the skin) or absence of a response (no difference on the skin) in the patch tests. Where there was getting red on the skin in the patch test result, marked differences in EDA were observed before and after drinking alcohol, while in the no difference on the skin in the patch test result, there were only small differences in EDA before and after drinking alcohol. Similar tendencies were observed in each classified type of EEG characteristics shown in Figures 7, 8 and 9.

DISCUSSION

We have clarified the mechanism of EDA, performing experiments using artificial cells, assuming that local ion exchange could result in fluctuations in EDA when drinking alcohol. The reported results were from experiments using artificial, rather than real cells. This study was based on the supposition that fluctuations in EDA upon consumption of alcohol would be caused not by the flow of ions inside and outside the local cell membrane but by nerve cells. It is believed that the channels and pumps in human cells are opened and closed by the brain's chain-of-command. Therefore, electroencephalograms were measured, and the results confirmed that fluctuations in the frequency band of electroencephalograms indicated both changes in the transmission system and EDA simultaneously. The channels and pumps transporting ions across the cell membrane are opened and closed by the brain's chain-of-command, while alcohol is absorbed or blended into the blood in the human body. As a result, the chain-of-command controlling the internal and external cell membranes becomes disordered, and ion concentrations change, finally causing EDA to change, confirming the above mechanism.

CONCLUSIONS

Fluctuations in electrodermal activity (EDA) before and after drinking alcohol are summarized as follows:

1. Electroencephalograms can be divided into three types: low frequency increases; high-frequency band increases; and no trends.
2. Large or small changes in EDA could be observed and the data range was sufficient for measurement.
3. The patch test is a simple method for examining alcohol tolerance.
4. The results from the patch tests corresponded to those from EDA experiments. In the presence of a response in the patch test, relative values of EDA become large. On the contrary, in the absence of a response in the patch test, differences between relative values become small.
5. EDA is produced by differences in ion concentration inside and outside the cell membrane, which can be considered to be caused not by local changes in ion concentration but by changes in the transmission of the brain's chain-of-command. As a result, it can also be presumed to have effects on EDA.

FUTURE WORKS

In the present study, it was clear that, knowing the EDA of each person under normal conditions, the relative changes from the initial values of EDA made it possible to detect alcohol. This experiment was performed with Japanese people. In the future, the reliability of data must be improved if the three test methods—EDA, electroencephalograms, and patch tests—are conducted for people of other nationalities. It is believed that this method will comprise an effective sensing system, through simplification of the sensing measurement system itself or reduction in cost.

ACKNOWLEDGEMENTS

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AUTONOMOUS EMERGENCY BRAKING TEST RESULTS

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ABSTRACT

Autonomous Emergency Braking (AEB) systems are becoming increasingly available on new vehicles as either standard fit or as an optional extra. AEB systems use sensors around the vehicle to detect potential collisions and warn or even intervene on behalf of the driver to prevent or mitigate the collision. A group of Insurance funded Research Centres, the AEB Group, authored a series of test procedures based on real world scenarios with the aim of introducing performance tests of these new technologies. Test procedures measure and rate system performance relevant to real world accidents and drive development of AEB systems. 11 different passenger car models from 2012 equipped with second generation AEB systems were tested to the AEB procedures. System performance is rated based on the quantitative response to incrementally more demanding scenarios and differences have been found in the efficacy of systems both in terms or sensor type and implementation. Assessment of system performance provides consumer groups and insurers with a clear indication of which systems may provide the greatest real world benefits.

INTRODUCTION

Various AEB systems have been on the market for a number of years, though mainly on high end luxury models as optional equipment. These AEB systems use RADAR, LIDAR and camera sensors either standalone or in combination to establish the range and movement of potential hazardous car and pedestrian targets. If a potential collision is identified, they provide a warning and/or braking response to help prevent the collision or reduce its severity.

In 2008 Volvo introduced a low cost standard fit laser based system that offered auto-braking (but no warning) at low speed up to 30km/h. The Insurance Institute for Highway Safety (IIHS) analysed insurance claims data to compare the Volvo XC60, which is fitted as standard with a low speed LIDAR system called City Safety, against other similar 4x4 models and other Volvos [1]. The study compared 22 mid-size 4x4s and showed that the XC60 had lower overall claim frequencies in all crash types; 27% reduction in third party damage claims, 22% in first party claims, and 51% reduction in personal injury claims. There are also two studies from AXA Winterthur [2] and Tristar [3] that showed rear-end crash reductions of 31% and 28% respectively.

A further study from IIHS [4] has shown the effectiveness of optional RADAR systems that also reduce crash rates by up to 14%; largely due to lower relevant crash population at higher speeds. These systems also offer a warning and can operate at higher speeds. When comparing the studies a range of effectiveness is found, but the overall trend is for reduced crashes involving vehicles with AEB systems.

Test procedures have been developed that aim to assess the performance of AEB systems in order to drive real world reductions in collision frequency and severity. The aim was to create a standardised set of conditions that would enable the objective, repeatable and reproducible assessment of AEB systems that would allow their performance to be reliably quantified in such a way that would reward more effective systems. This paper summarises the development of those test procedures from accidentology studies. As part of the development and validation of those test procedures, a range of vehicles have been tested. This paper also aims to give an insight into the range of performance identified in this testing.

REAL WORLD ACCIDENTOLOGY

Analysis of real world crash events enabled the AEB group to study the most common crash types to ensure the test procedure addressed a target population relevant to these technologies. The development of these procedures is described in more detail by [5] [6] [7] but is summarised here.

In order to define test scenarios that are representative of real-world collisions, an accidentology study was completed on behalf of the AEB Group by Loughborough University [5]; this report formed the basis of the analysis. It used two major sources of information describing crashes in Britain: the national accident database

STATS 19 [8] and the in-depth On-the-Spot study (OTS) [9].

The exact methodology used to derive the clusters can be reviewed in the report from Loughborough University [5] or in [6]. In summary, the accidents were identified as being a Car-to-Car Rear (CCR) accident and then a cluster analysis was performed to group them mathematically according to common features. The datasets used for the cluster analyses of STATS 19 were derived directly from the source files by programmed computer logic; whereas the summary datasets used for OTS were compiled by analysts who completed a full accident reconstruction and based their assessment on the full range of materials contained in the OTS case files. In order to help define the most important features of that cluster so that they could be used to generate test scenarios a Chi-squared test was used to identify the features of the scenarios that were statistically over-represented.

The cluster analysis of STATS 19 was taken as a nationally representative result for the UK, and the OTS clusters also showed a similar trend. More importantly the additional case reconstruction evidence from OTS was used to provide additional detail about the UK accidents that could not be provided by the STATS 19 database. This additional detail from the OTS case reconstructions includes braking responses, overlaps between vehicles, and analysis of the travel and impacts speeds and headway conditions.

The next stage in defining the test scenarios was to move from a range of accident clusters to an initial definition of test scenarios. The STATS 19 clusters indicated too many CCR accident scenarios to be practically feasible for completion in one test day, which is the preferred time for practical requirements of a consumer/insurer test program. Therefore some clusters were either amalgamated or discounted as testing scenarios for two reasons; low frequency of occurrence or practical difficulties in test implementation. The test scenarios that were selected cover 73% of real world CCR collisions, and are summarised as a Car-to-Car Rear collision against a stationary target, angled stationary target (for future development), moving target and braking target.

OTS was then used to verify this selection of test scenarios, and to add further detail such as speeds and headways. For example, cluster 1 of the OTS CCR cases shows a mean approach speed of 41km/h toward a stationary target. However the sensor technology developments mean that avoidance up to 50km/h is feasible, so 50km/h was selected as the upper speed for the CCR stationary (CCRs) test, so called the ‘CITY’ test.

The CCRs was given an additional speed range for approaches at 50-80km/h, and called the ‘INTER-URBAN stationary high speed’ test. The terms ‘City’ and ‘Inter-urban’ are used to help aid consumer understanding of the type of collisions that the systems are addressing, and the speed ranges and conditions of the test.

The ‘INTER-URBAN moving’ (CCRm) test scenario for a moving target was defined as a target moving at 20km/h, with approach speeds 50 to 80km/h, and these speeds were similarly drawn from the accidentology study.

The ‘INTER-URBAN braking’ (CCRb) test represents a braking (decelerating) target car. Both test and target vehicles are moving at 50km/h based on the OTS data. A matrix of four tests was devised to represent a two headway conditions: a long headway of 40m, and a short headway of 12m typical of the following distance in busy traffic; and two braking conditions: $2m/s^2$ to represent the levels of braking in normal driving, and $6m/s^2$ to represent emergency braking.

The next stage in the selection of test scenarios was to carry out some international comparison to ensure that the scenarios selected for the UK are also relevant to other nationalities. UDV reported on their analysis of insurance claims from Germany, and an accidentology workshop by the vFSS reported on analysis of GIDAS (an accident investigation and reconstruction database); this data was used in comparison against the UK data. The frequencies for the different test scenarios were accepted as reasonably comparable, and more importantly there have been many stakeholder meetings regarding the selection of test scenarios since this area of work began in 2009, and these test scenarios are now widely accepted in the industry.

The final stage in definition of the test scenarios was to consider whether just a single point test was required, e.g. CCRs CITY at the highest speed 50km/h, or whether a range of speeds was required. Whilst safety testing of vehicles in consumer assessment programs has typically been limited to a single test speed; with AEB testing there is opportunity to run repeated tests over a speed range. The advantage of testing over a speed range is that the range of system performance can be assessed. In particular testing over a speed range can better represent the speed range of collisions occurring in the real world, and can be used to identify any subtle performance differences between systems. There are also practical reasons for running tests over a range of speeds: firstly for the safety of the test driver since it is safer to start with tests at a low speed and gradually increase the speed; and secondly since additional runs at different speeds are not a large time burden in comparison with changing test scenarios. Therefore it was decided to include a range of speeds were possible for the stationary and moving target tests.

The test scenarios have been widely accepted in the industry, and although there have been some variations in the exact speed ranges selected since [7], the overall test scenarios remain the same. This paper describes the latest status of the test procedures.

TEST SCENARIOS

Analysis of the real world accident data has helped to generate four accident scenarios that were used as the basis of the AEB tests:

Table 1. AEB Test Scenarios

Test type		**Illustration**	**Test description**
CCRs CITY Stationary low speed	Car drives into stationary vehicle (low speed)		Approaching a stopped vehicle at test speeds from 10 to 50km/h in 5km/h increments.
CCRs INTER-URBAN Stationary high speed	Car drives into stationary vehicle (high speed)		Approaching a stopped vehicle at test speeds of 30 to 80km/h in 5km/h increments.
CCR INTER-URBAN Slower moving	Car drives into slower moving vehicle		Approaching a moving target at 20km/h. Test vehicle speed 50km/h up to 70km/h in 5km/h increments.
CCR INTER-URBAN Braking	Car drives into braking vehicle		Approaching a decelerating target, both vehicles initially moving at 50km/h. Target car has two headway conditions (short 12m and long 40m) and two braking levels (normal $2m/s^2$ and emergency $6m/s^2$).

The test scenarios in this procedure are applicable to passenger cars with an Autonomous Emergency Braking (AEB) system or Forward Collision Warning (FCW) system. They are valid only for vehicles where the detection system responds to the visual, RADAR or reflective (LIDAR) signature of the rear of a passenger car.

TEST TARGET

The ability of the test target to accurately represent the characteristics of a real vehicle in the eyes of a variety of different sensor types was quickly recognised to be a critical part of a realistic, technology neutral test to drive real world safety improvements. The AEB group used information from a vehicle with sensor fusion (RADAR and camera) and took outputs from the vehicle CAN bus to identify the confidence with which the AEB sensors recognised a variety of different vehicle test targets proposed by a variety of organisations and compare them with real vehicles. The results are summarised in *Figure 1* below. The test illustrated shows the output from the sensors, where the outputs are green high confidence in the target threat is shown. When coloured red there is a low confidence, and where no colour is shown neither RADAR nor camera registered a threat.

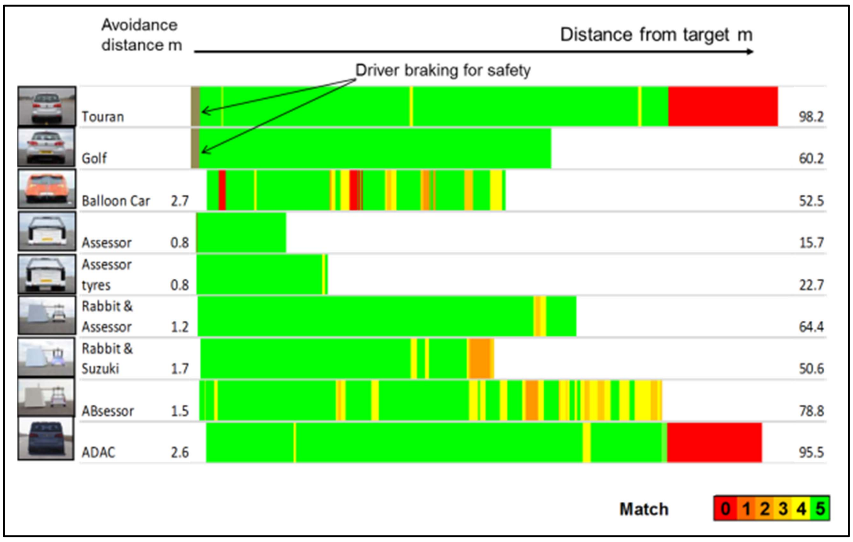

Figure 1: Confidence with which a radar camera AEB system detected a range of vehicles and test targets.

It can be seen that the device with the closest match to a real vehicle was that termed the ADAC target. This target was developed by Continental and was improved by ADAC for use in AEB testing. This was further developed by Thatcham to include the correct visual characteristics to accommodate camera based systems. This target was subsequently adopted by the AEB and Euro NCAP group as a suitable AEB evaluation target. Its development is covered in a separate paper.

TEST PROCEDURE

Having defined the scenarios that needed to be assessed in order to reflect real world accident situations and identified a realistic and practical test target, the next step was to define the detail of the test procedure itself. The aim was to provide accurate and repeatable results while minimising the test burden. As such, the procedure starts with the lowest test speed specified for the particular scenario. Test speed was then increased in 10km/h increments until a test speed is reached where the AEB system no longer avoids the collision and an impact occurs between the test vehicle and car target. At this stage, the test is repeated at a speed 5km/h lower than that in which the impact occurs. AEB performance is measured in all test scenarios. For Inter-Urban test scenarios CCRs, CCRm and CCRb, an additional assessment of the vehicle FCW system (if present) was also undertaken. The process for determining the tests to be undertaken is shown in *Figure 2*.

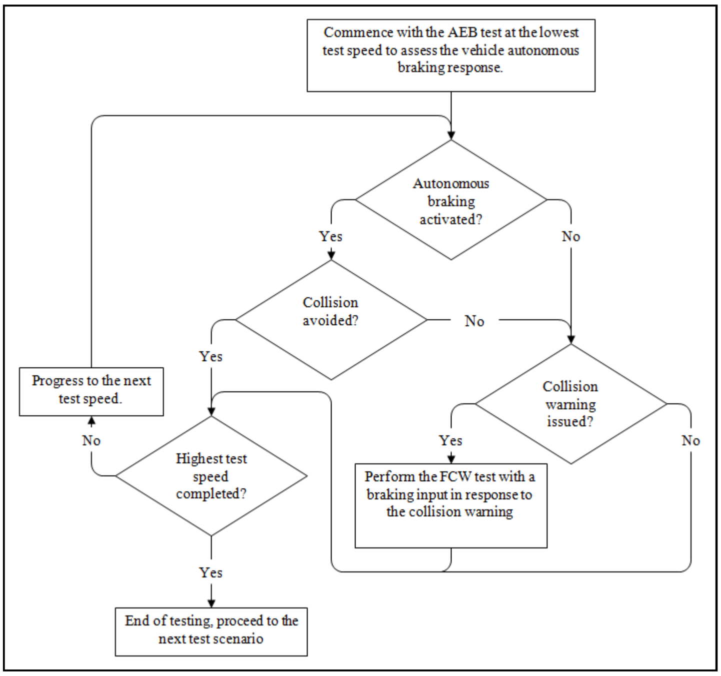

Figure 2. Flow diagram for AEB testing.

The aim of the test is to replicate an inattentive driver. For this reason, it is important to have constant inputs immediately before the test because it was considered possible that some AEB systems may take variation in driver inputs as evidence that they were alert and this information may be used to influence the reaction of the driver assistance. The tests are also relatively complex, particularly in the inter-urban scenario requiring the speed and alignment of two vehicles to be tightly controlled relative both to absolute requirements and to each other as well as requiring defined braking inputs from both the target vehicle and the test vehicle (response to FCW). Each of these variables was found to have the potential to influence the results from the system and as such some very restrictive tolerances were targeted, for example:

- Target consistency limits (CCR lead vehicle stopped and CCR lead vehicle decelerating)
  - Speed +1.0km/h
  - Lateral position ±0.10m
  - Yaw rate ±1.0º/s
  - Deceleration ±[0.5]m /s^2
- Test vehicle approach consistency limits
  - Nominal test speed +1.0km/h
  - Steering wheel velocity ±10 º/s
  - Accelerator pedal position ±5%
  - Lateral position ±0.10m
  - Yaw rate ±1.0º/s
  - Headway +1.0m

It was found that it was not feasible to reliably meet this type of test tolerance, and thus ensure accuracy and repeatability, with human drivers and thus robotic control of steering, accelerator and brake was required. Thatcham has used path following steering and combined brake and accelerator robot from Anthony Best Dynamics as shown in Figure 3.

Figure 3. Combined Brake and Accelerator robot (CBAR) and steering robot used to control the test vehicle.

RATING SYSTEM

The final part of the development of the AEB procedures was defining a scheme for scoring the performance of different vehicles. This development has been described in more detail by Schram *et al* [10].

EVALUATION VEHICLES

Eleven vehicles have been assessed either as part of final validation of the test procedure, as part of the UK insurers Group Rating programme, or for Euro NCAP Advanced awards. The vehicles and the technologies they use are defined below:

- Ford Focus: LIDAR sensor
- Mazda CX-5: LIDAR sensor
- FIAT Panda: LIDAR sensor
- Mazda 6: LIDAR sensor
- FIAT 500L: LIDAR sensor
- VW UP!: LIDAR sensor
- Volvo XC60: LIDAR sensor
- Mitsubishi Outlander: RADAR sensor
- Volvo V40: LIDAR sensor (standard fit)
- Volvo V40: LIDAR, RADAR and Camera sensor fusion (optional fit)
- Subaru Outback: Stereo camera fusion

RESULTS

Most of the vehicles tested so far have been equipped with low speed systems and as such the results presented here have been restricted to those from the City test. Performance is characterised by the initial test speed and the actual impact speed, effectively the speed reduction. An example of this is shown in Figure 4 below.

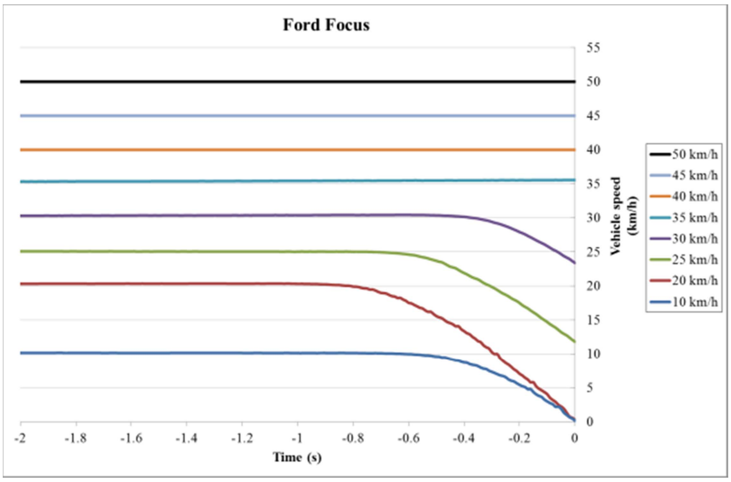

Figure 4. Example of results presentation.

The graph is a time history of individual test runs and T_0 is the time at which either an impact occurs with the target or the vehicle comes to rest. Thus, the example above shows that the Ford Focus system avoided a collision entirely from initial speeds of 10km/h and 20km/h, mitigated the collision from initial speeds of 25km/h and 30 km/h and had no effect at speeds of 35km/h and above.

These results have been calculated for each vehicle and then grouped by the sensor technology used.

LIDAR

Analysis of the results from the 8 LIDAR only systems (see Figure 5 to
Figure 12 below) showed several distinct groups.

The Mazda 6, the Fiat 500L and the VW Up! were all found to have systems that had no effect at speeds of 30km/h or above. The 500L and the Up! fully avoided collisions at all speeds less than this, whereas the Mazda 6 just failed to avoid the collision at 25km/h.

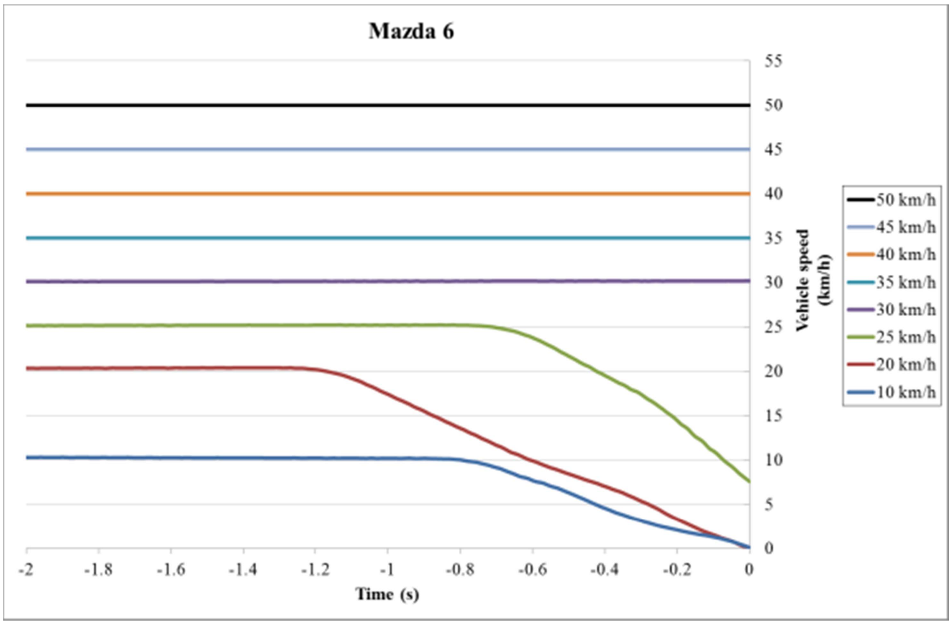

Figure 5. Time history for Mazda 6 tests at each test speed.

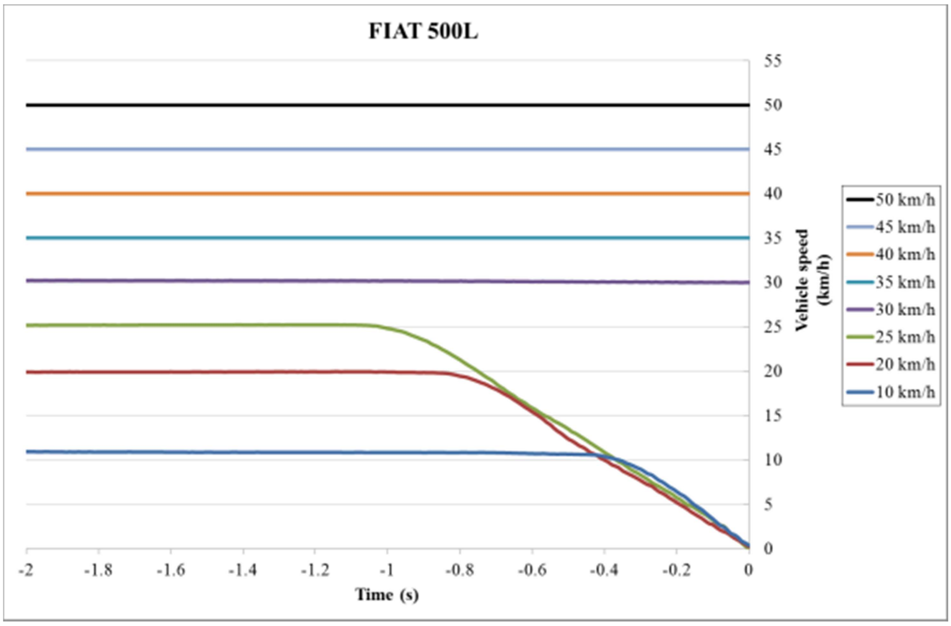

Figure 6. Time history for Fiat 500L tests at each test speed.

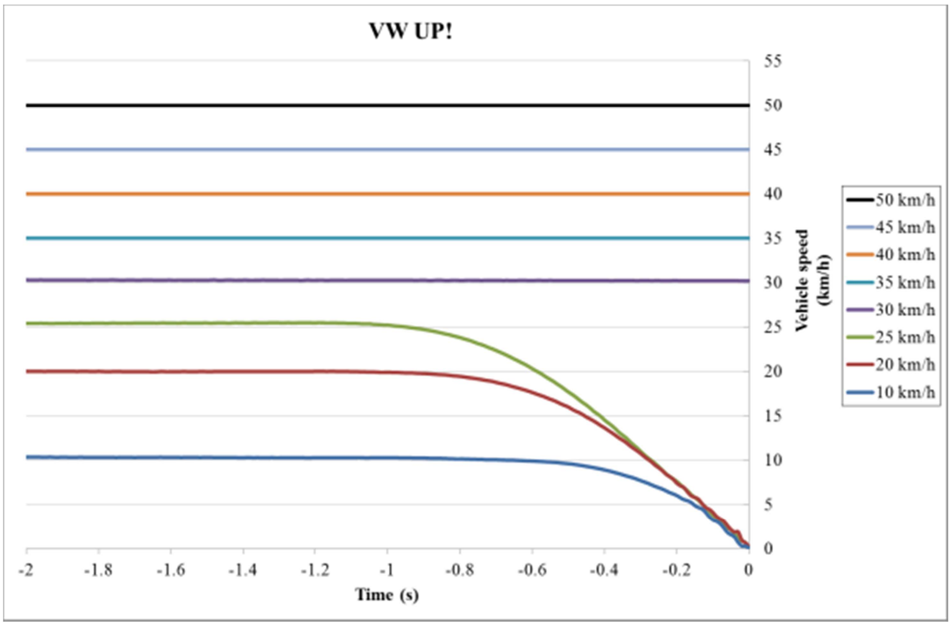

Figure 7. Time history for VW Up! tests at each test speed.

The next performance group was formed by the Mazda CX-5, the Ford Focus and the Fiat Panda. For each of these vehicles the systems had a mitigation effect at 30km/h (one test speed increment higher than the first group). However, despite the extra effects at 30km/h, the CX-5 and the Focus only mitigate the collision at 25km/h whereas the Up! and the 500L fully avoid at that speed.

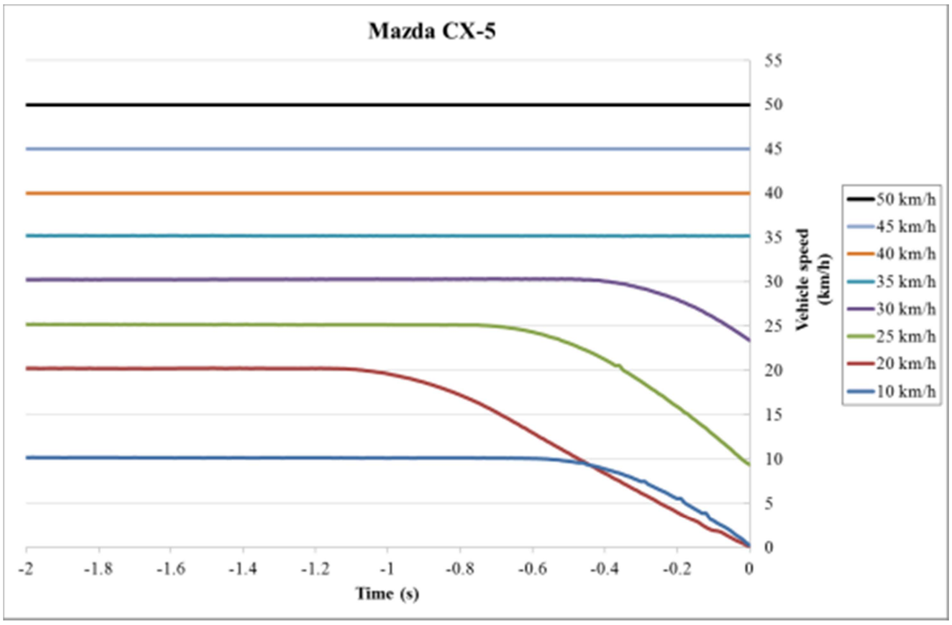

Figure 8. Time history for Mazda CX-5 tests at each test speed.

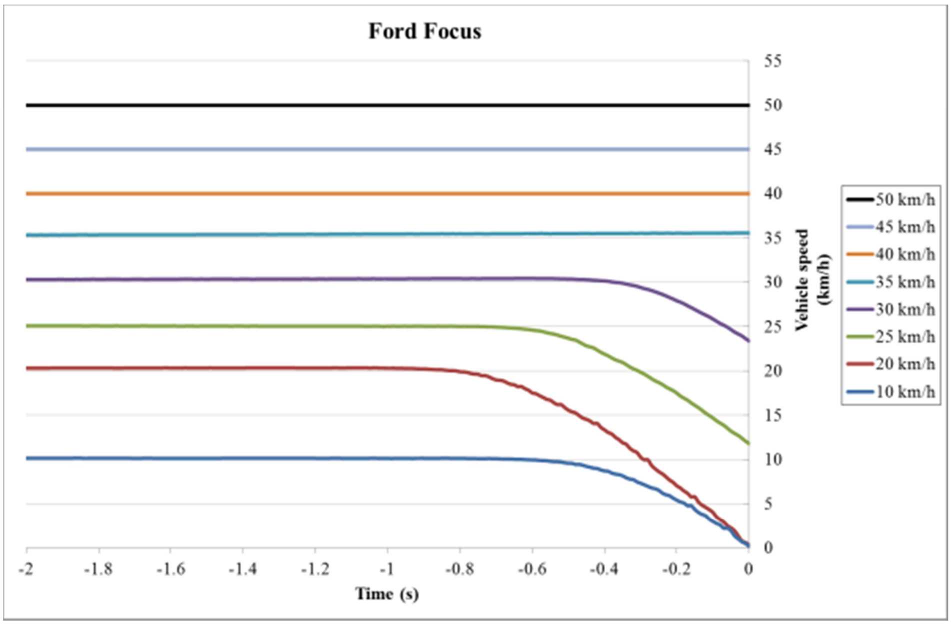

Figure 9. Time history for Ford Focus tests at each test speed (same as *Figure 4*).

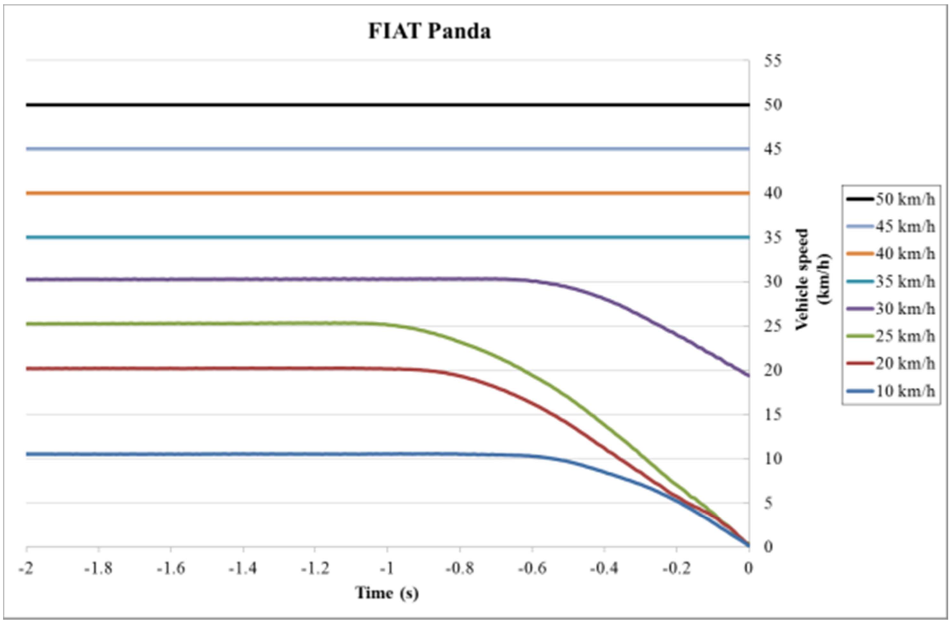

Figure 10. Time history for Fiat Panda tests at each test speed.

The final group of vehicles, both Volvo's, offer some function at test speeds right up to 45km/h, though the speed reductions involved are very small at test speeds of 35km/h and above. Again, these systems will avoid only up to 20km/h.

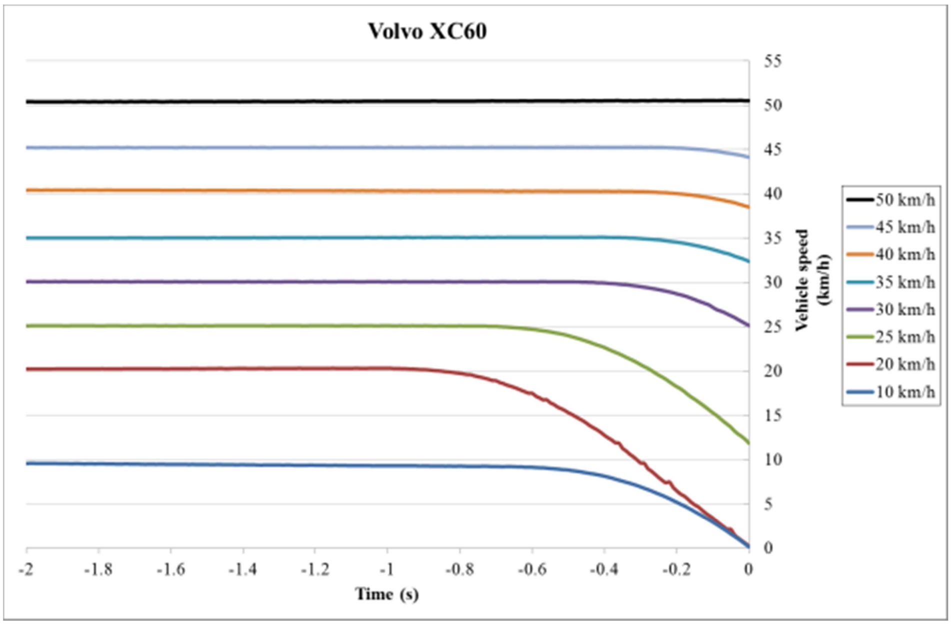

Figure 11. Time history for Volvo XC60 tests at each test speed

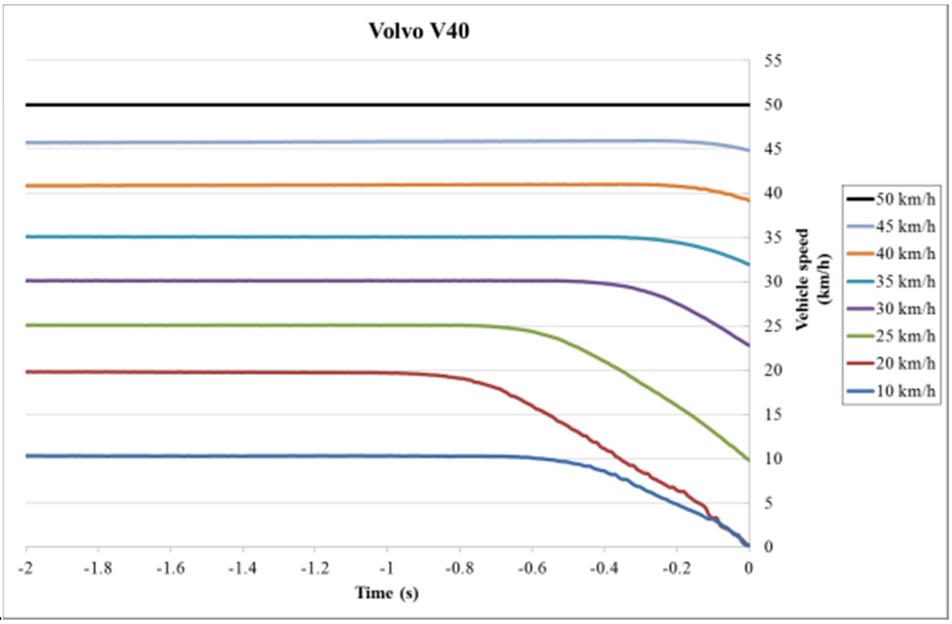

Figure 12. Time history for Volvo V40 (standard fit) tests at each test speed.

The results suggest significant variation in the implementation of the system even within the same sensor technology. The limited comparisons available also suggest that this variation is not brand specific with Fiat and Mazda both having different levels within their range.

The main difference between the groups appears to be the time at which the sensor reacts. For all those systems that avoid at 25km/h, it can clearly be seen that speed reduction commences progressively earlier as test speed increases from 10km/h to 20km/h and then 25km/h. At a test speed of 25km/h, braking commences approximately 1 second before the vehicle comes to rest.

For the vehicles that fail to avoid at 25km/h, it can be seen that speed reduction only commences at a time closer to the point of collision, typically around about 0.6 seconds before impact. The same systems react earlier at 20km/h. This suggests that the reason for the difference is some function of sensor range and the time required to process data and to initiate braking.

RADAR

The Mitsubishi Outlander is the only vehicle in the sample using a RADAR only system to achieve AEB functions in the City test. It can be seen that this system falls into the category of system that either avoids fully or has no effect. However, this RADAR system offers full avoidance from 30km/h, 5km/h greater than any of the LIDAR systems could offer.

It can also be seen that this is achieved by early reaction. At 25km/h the reaction time is similar to the LIDAR systems that avoided at the same speed (approximately 1 second). At 30km/h, braking commences at around 1.5 seconds before the impact point.

A further notable difference with the Mitsubishi implementation is that there is a noticeable two-phase deceleration profile; moderate deceleration in the first phase of braking followed by a step increase as the target approaches. This can be seen as the change in the slope of the time history and may possibly be seen as mitigating any risks of unintended consequences arising from the earlier intervention strategy.

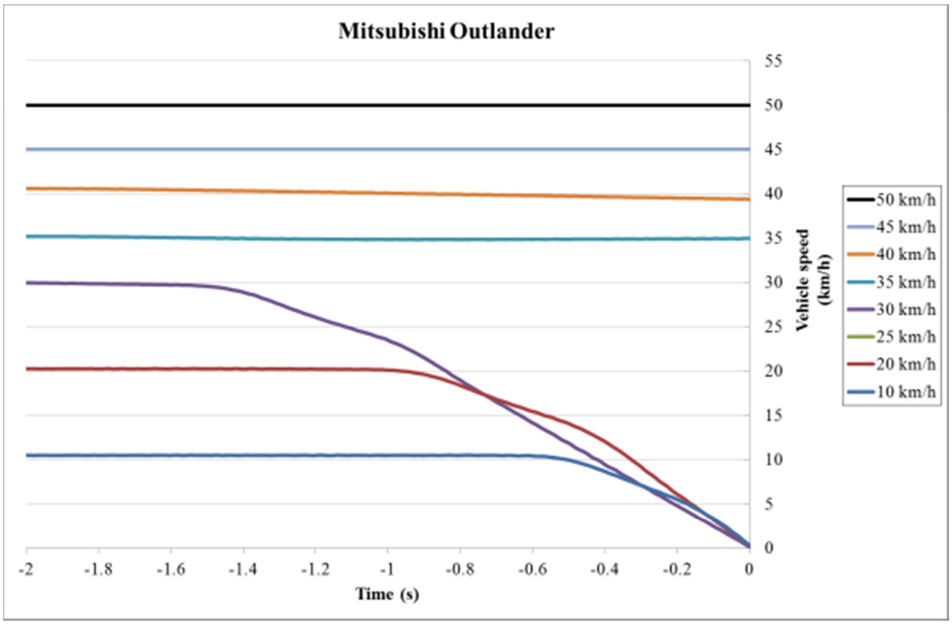

Figure 13. Time history for Mitsubishi Outlander tests at each test speed.

LIDAR/RADAR/camera fusion

The Volvo V40 has a LIDAR system as standard fit and a test of this system was reported in the LIDAR section. It is also possible to optionally add a RADAR and a camera to the LIDAR system to create a 3-way sensor fusion system, known as CADS III+. This system is also capable of pedestrian AEB, though this functionality is not assessed in this paper.

The sensor fusion system on the V40 offers full avoidance from speeds of up to 35km/h and strong mitigation from speeds right up to 50km/h. Again, the time at which the brake system reacts is a significant factor with braking commencing at approximately 1.2 seconds before impact at both 30km/h and 35km/h. This also shows deceleration is a factor; the system reacts later than the Mitsubishi but still avoids at a higher speed.

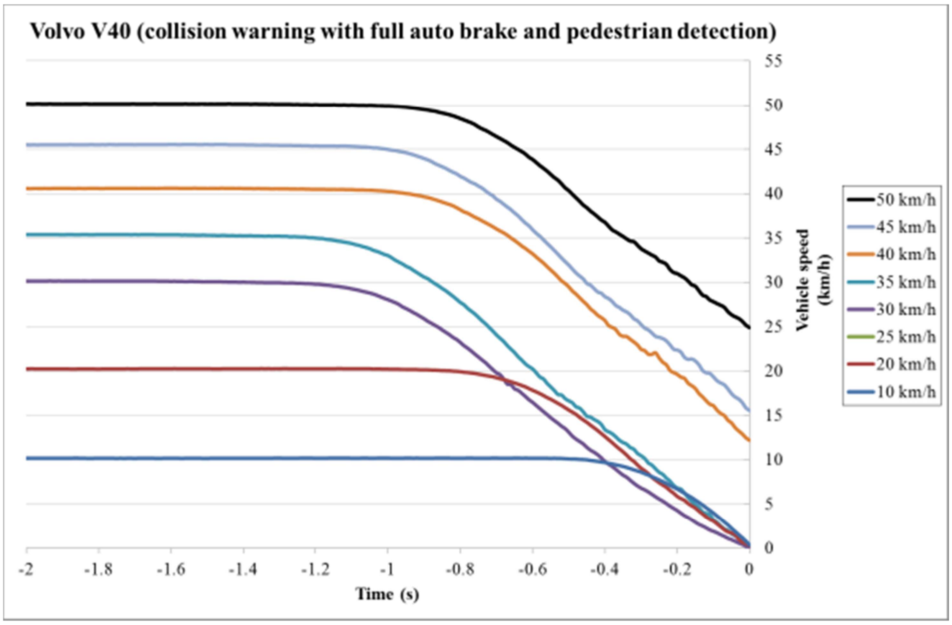

Figure 14. Time history for Volvo V40 (Optional fit CADS III+) tests at each test speed.

Stereo Camera

The Subaru Outback is the only vehicle in the sample equipped with a Stereo Camera system and it should be noted that the example tested was an imported Japanese specification not available in the UK. The stereo camera system is also capable of pedestrian AEB. This vehicle achieved the highest performance level from the sample tested, with full avoidance achieved at 50km/h. The system shared the two phase deceleration strategy with the Mitsubishi Outlander but reacted even earlier and decelerated harder at the higher speeds.

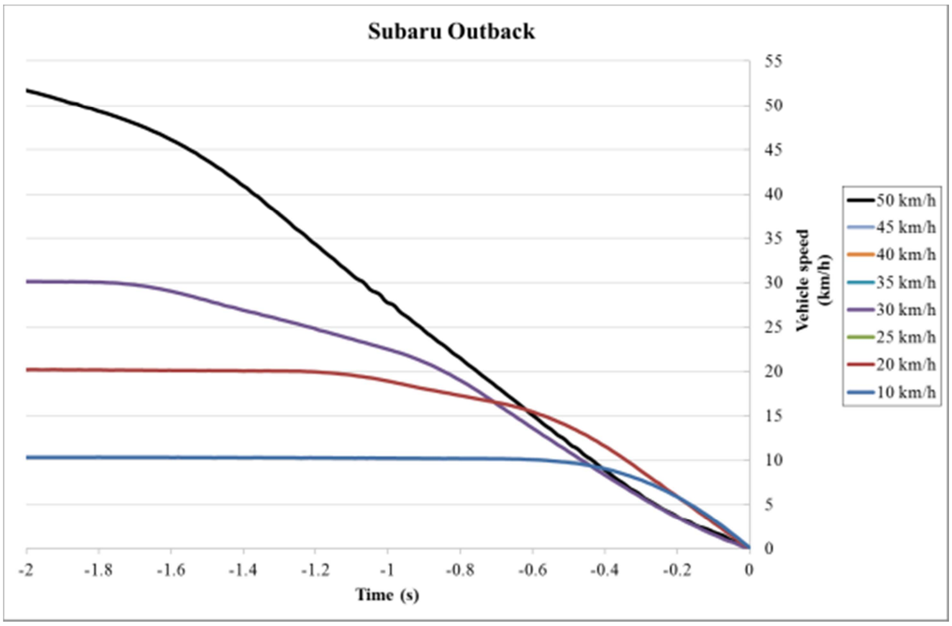

Figure 15. Time history for Subaru Outback tests at each test speed.

DISCUSSION

Test procedures have been rigorously developed based on real world accident scenarios and these have been shown to be capable of accurately and repeatably assessing the effectiveness of AEB and FCW systems in both low and high speed traffic situations. Tests undertaken according to the newly developed protocol have shown that there is quite a wide variation in the performance of current production AEB systems. This variation is related to the technology employed but variation in the implementation strategies is also apparent even within individual technology groups. This has been summarised in *Figure 16* below, which shows the time histories for the highest test speeds at which full avoidance was achieved by each vehicle in the City test.

It can be seen that the more sophisticated multiple sensor systems capable of pedestrian detection also offer the best performance in the Car to Car Rear test (city).

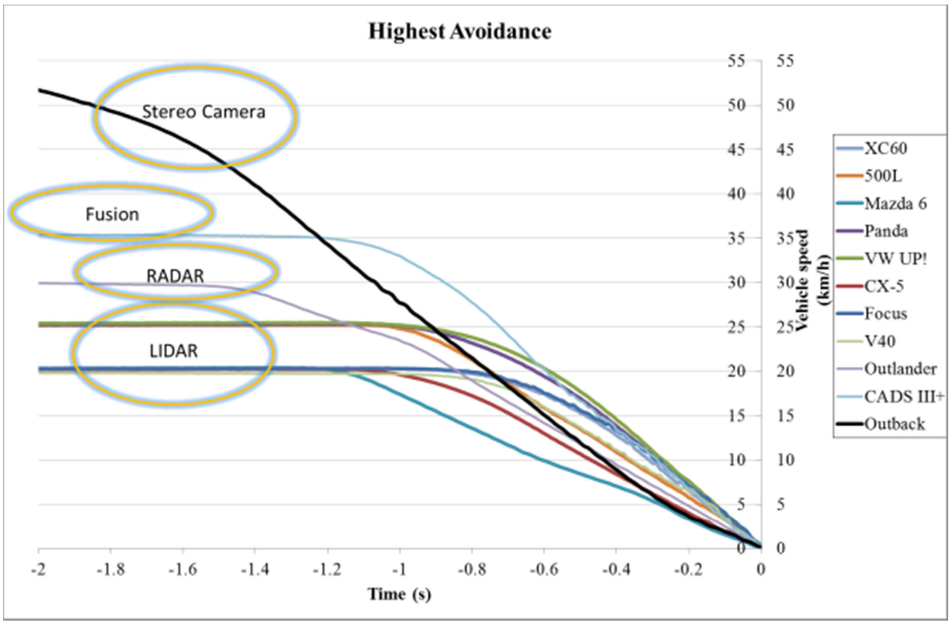

Figure 16. Time history for the highest avoidance speed for each vehicle.

There are some limitations of this study. The vehicles tested in this paper are representative of the current AEB systems fitted and available from major manufacturers and across vehicle segments, but they may not reflect the performance of all different types of systems implemented on models on the current market. Also, since the assessment is based on comparative testing within the scope of the test scenarios no comment can be made on the how system performance would differ outside of these scenarios; however the AEB test procedures are highly relevant being based on statistically significant scenarios from accident data [5] [6] [7].

CONCLUSIONS

AEB systems are becoming more popular and have a positive effect on real world crash rates. There is a need to provide information to consumers on the effectiveness of these systems. Test procedures have been developed to reflect the most important accident configurations for Car-to-Car Rear. These tests can be used to assess the performance of both AEB and FCW systems and are expected to be a strong driver of improved safety in the real world.

Eleven vehicles have been assessed in the city tests and variations have been found in performance both between different technology solutions, but also in the way a particular technology is implemented.

LIDAR systems can be broadly categorised in three groups; those that avoid up to 25km/h and have no effect at 30 km/h or above; those that avoid up to 20km/h, mitigate to 30km/h and have no effect at 35km/h or above; and those that avoid up to 20km/h and mitigate at least small amounts from speeds of up to 50km/h.

One RADAR-only system has been tested and was found to offer higher speed avoidance (up to 30km/h) than any of the LIDAR systems but this had no mitigation effect at higher speeds. Two multiple sensor systems were tested and both offered greater performance than either LIDAR or RADAR alone. The stereo camera system was most effective, with full avoidance from test speeds of up to 50km/h.

The way in which the speed reduction is achieved by vehicles also varies significantly. The time to collision at which the vehicle begins to brake varies most significantly but the level of deceleration also differs.

The AEB test procedures referred to in this paper have been adopted by Euro NCAP (European New Car Assessment Programme) to form the basis of their AEB assessment from 2014 [10]. The UK insurance Group Rating Panel has also adopted the ‘City’ test (CCR test towards a stationary target at low speed) from 2012. Assessment of system performance provides stakeholders with a clear indication of which systems provide the greatest real world and cost benefit.

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European project AsPeCSS - interim result: Development of Test Scenarios based on identified Accident Scenarios

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ABSTRACT

Within this paper different European accident data sources were used to investigate the causations and backgrounds of road traffic accidents with pedestrians. Analyses of high level national data and in-depth accident data from Germany and Great Britain was used to confirm and refine preliminary accident scenarios identified from other sources using a literature review. General observations made included that a high proportion of killed or seriously injured pedestrian casualties impacted by cars were in 'dark' light conditions.
Seven accident scenarios were identified (each divided into 'daylight' and 'dark' light conditions) which included the majority of the car front-to-pedestrian crash configurations.
Test scenarios were developed using the identified accident scenarios and relevant parameters. Hypothetical parameters were derived to describe the performance of pedestrian pre-crash systems based on the assumption that these systems are designed to avoid false positives as a very high priority, i.e. at virtually all costs. As result, three 'Base Test Scenarios' were selected to be developed in detail in the AsPeCSS project. However, further Enhanced Test Scenarios may be needed to address environmental factors such as darkness if it is determined that system performance is sensitive to these factors.
Finally, weighting factors for the accident scenarios for Europe (EU-27) were developed by averaging and extrapolation of the available data.
This paper represents interim results of Work Package 1 within the AsPeCSS project.

INTRODUCTION

Background

In 2009, 6,641 pedestrians were killed in road traffic accidents in the EU-24[1], which is about 20% of all fatalities. This equates to an average rate of 13.6 pedestrians killed per million inhabitants, which varies by member state from the lowest of 3.8 pedestrians killed per million inhabitants in the Netherlands to the highest of 47.2 in Romania. In 2009, nearly half (46%) of all pedestrian fatalities in the EU-24 states occurred during dark light conditions (varying between 94% in Ireland and 35% in France) and another 6% in twilight [1].
The German national road traffic statistics show that in the year 2008, 653 pedestrians were killed in Germany, but this number had fallen to 476 in 2010. This was the lowest value since the start of the statistical recordings. However, this number had again risen to 614 in 2011. The number of 614 killed pedestrians was accompanied by 8,854 seriously injured and 27,542 slightly injured pedestrians. In addition, the accident statistics report that in case of pedestrian fatalities older people (65+ years) constitute to nearly half, which

[1] Data available from member states of the European Union EU-27 without Bulgaria, Cyprus and Lithuania

shows that this group is over-represented for pedestrians [2].
Generally, pedestrians cross streets wherever it is convenient and possible, which is not necessarily at pedestrian crossings. Because of this, EuroTest [3] investigated, by means of national statistics for 2005 for various European countries, the incidence of pedestrian accidents with fatalities on and outside pedestrian crossings. In conclusion, a significant diversity of results was shown for the different countries in combination with no significant correlation to 'rules and directives governing the right of way' or the 'pedestrian crossing planning and design'. However, the major differences in European countries were found to be related to basic elements such as traffic law duties of pedestrians and motorists at pedestrian crossings, the national criminal fines and catalogues and the interpretation of the types of crossings.
An APVRU study [4] evaluated "near miss crashes" and found that the accident risk depends strongly on local situations, the flow of traffic and the crossing facilities. Furthermore, pedestrian inattention was identified as the main causative type of behaviour in case of accidents. Elderly also tend to require more time to cross the road and estimate speeds and distances less accurately.

European FP7 project AsPeCSS

The overall objective of the European FP7 project AsPeCSS (Assessment methodologies for forward looking integrated Pedestrian and further extension to Cyclist Safety Systems) is to contribute towards improving the protection of vulnerable road users, in particular pedestrians and cyclists, through the development of harmonised test and assessment procedures for forward-looking integrated pedestrian safety systems. These procedures will take into account the system's pre-crash braking and passive safety components and will be benefit based. Within Work Package 1 accident scenarios and associated test scenarios with weighting factors have been developed for the assessment of the pre-crash braking component of integrated pedestrian safety systems.

Objective

The objective of the work described in this paper was to identify accident scenarios and develop associated test scenarios for the assessment of the pre-crash braking component of integrated pedestrian safety systems.

METHODS AND DATA SOURCES

To identify accident scenarios results from previous projects (e.g. European FP7 project APROSYS, AEB Test Group, vFSS) were reviewed and further extensive analysis of national and in-depth car-to-pedestrian accident data from Germany and Great Britain (GB) was performed (note: for full information please see [5]).
The Autonomous Emergency Braking (AEB) Test Group comprises several insurer-funded research centres. Outline test procedures were published by the group in 2011 [6].
The vFSS group ("advanced Forward-looking Safety Systems") was founded to develop technology independent test procedures for primary safety driver assistance systems (in particular advanced emergency braking systems), which reflect the real accident situation. The project consortium consists of several car manufacturers, the German insurance association and BASt.

The German national road traffic statistics cover accidents which were reported to the police. Pursuant to Article 1 of the German law on statistics of road traffic accidents only those accidents are recorded which are due to vehicular traffic, i.e. accidents involving pedestrians only, are not covered by these statistics. Survey records for the statistics of road traffic accidents are the copies of the standard traffic accident notices (Verkehrsunfallanzeigen) as used for the entire Federal Republic which are completed by police officers attending the scene of the accident.
In contrast to this, i.e. recording of all personal injury accidents with a low level of detail, GIDAS (German In-Depth Accident Study) is devoted primarily to the task of documenting a representative sample of individual road traffic accidents with a high level of detail. In this study, GIDAS data from year 2000 to 2011 were used.

STATS19 is the reported road traffic injury accident database in Great Britain, established in 1949. Data is collected in England, Scotland and Wales by police using a standardised STATS19 data gathering form. Police are required to attend every road traffic accident that involves an injury and whilst on scene, officers fill out a series of standard forms. In this study, STATS19 data from 2008 to 2010 were used to determine the proportion of pedestrian casualties in each accident scenario. The number of killed or seriously injured casualties was of particular interest.

Weighting factors to indicate the relevance of the accident scenarios were also calculated for Europe. Finally, test scenarios based on these accident scenarios were developed. This work considered basic physics and contributing factors such as the age of pedestrians, speed data of the parties, societal factors, light and weather conditions. With the novel approach taken it was found that some test scenarios were relevant for a number of accident scenarios.

Definitions

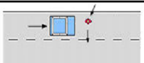
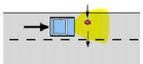
In this paper ‘darkness’ and ‘dark light conditions’ includes both the darkness and twilight conditions specified in the national databases, unless stated otherwise.
An Accident Scenario is defined as a crash configuration (general motion of vehicle and pedestrian) together with key surrounding conditions (e.g. road layout, view of pedestrian obstructed or not, dark or light).
A Test Scenario is a test configuration which reflects the characteristics of one or more accident scenarios which are key to the performance of the pedestrian safety system.

ACCIDENT DATA REVIEW

Results from Previous Projects

A first estimation for accident scenarios was made based on the results of the work performed by APROSYS, the AEB Test Group and vFSS (for details please see [5]).
The scenarios proposed by the AEB Test Group were defined predominantly by analyses of British collision data (with supplementary analyses of German data). The principal collision data analysis used a cluster analysis technique to identify groups of collisions with similar characteristics. Two separate cluster analyses were performed; the first used the national STATS19 database for Great Britain, and the second used the (in-depth) On-The-Spot (OTS) database. Table 1 shows the key accident scenarios identified within the AEB project for killed, killed and seriously injured (KSI) and all injured pedestrian casualties.

Table 1: Accident scenarios from AEB project

No	Accident Scenarios	Description	Representativeness (%) Killed	KSI	All
1		Pedestrian walking; Daylight, fine; vehicle going ahead; 10-30mph speed limit; mid-size pedestrian; crossing especially from near-side; Not obstructed	24	34	39
2		Pedestrian running; Daylight, fine; vehicle going ahead; 10-30mph speed limit; small pedestrian; crossing especially from near-side; obstructed	4	13	14
3		Pedestrian walking; Darkness, not fine; vehicle going ahead; 10-30mph speed limit; large pedestrian; crossing either direction; not obstructed	41	28	21
4		Pedestrian walking; Darkness, fine; vehicle going ahead; mid-size pedestrian; stationary or along; not obstructed	14	5	3
		TOTAL	83	80	77

An overview of key scenarios identified by the vFSS project is provided in Figure 1. Lateral crossing scenarios with and without obstructions formed the largest proportions.

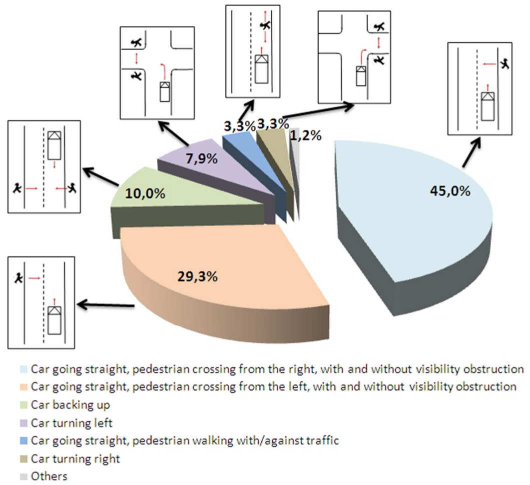


Figure 1: Key accident scenarios identified by the vFSS group [7]

These results were merged to form preliminary accident scenarios (see Table 2), that served as a basis for further development.

Table 2: Preliminary Accident Scenarios for AsPeCSS (derived from previous projects)

ID	Accident Scenario Description
1 A/B	Crossing straight road, nearside, no obstruction, day/dark
2 A/B	Crossing straight road, offside, no obstruction, day/dark
3 A	Crossing at junction, nearside, vehicle turning across traffic, day
4 A	Crossing at junction, nearside, vehicle not turning across traffic, day
5 A/B	Crossing straight road, nearside, obstruction, day/dark
6 A/B	Crossing straight road, offside, obstruction, day/dark
7 A/B	Along straight road, no obstruction, day/dark

ACCIDENT DATA ANALYSIS

At this point, additional information was needed and thus further investigations were performed using current data from Germany and GB to identify accurately the weighting for the preliminary accident scenarios identified above and to check their appropriateness. It should be noted that French national accident data was also used for the analysis but it is not reported in this paper because it added little to the analysis due to the limited extent of the data. For full information please see [5].

Results Germany

The analyses of German national accident data were used to identify common accident scenarios of car-to-pedestrian crashes and appropriate weighting factors for them. The analysis involved the identification of all pedestrian casualties involved in crashes with a car and the examination of the characteristics of the target population; in particular to determine the proportion injured in each of the preliminary accident scenarios defined.
Investigation of road traffic accidents with personal injuries involving pedestrians in Germany in 2011

shows that pedestrian accidents mostly occur in urban areas with a share of 94 % (31,168 accidents), rather than non-urban (country) areas (6 %, 1,832 accidents). Table 3 shows the numbers and proportions of injured pedestrians in 2011 with their injury severity (includes multiple counting since one accident can contain multiple road user types). The proportion of pedestrians injured in built-up areas (around 94 % of the total casualties) compared to the proportion killed (69%) indicates that although the greater proportion of accidents occur in built-up areas, the ones that occur in non-built-up areas are more injurious [2].

Table 3: Vehicle-to-Pedestrian casualties in Germany in year 2011

Pedestrians	Total		Killed		Seriously injured		Slightly injured	
Urban roads	34,708	94%	434	69%	8,179	92%	26,095	95%
Out of town	2,313	6%	191	31%	675	8%	1,447	5%
Total	37,021	100%	625	100%	8,854	100%	27,452	100%

According to the official statistics, traffic accidents involving pedestrians (two parties) mostly occur with passenger cars. In 2011 there were 22,160 accidents in this case (73%) of a total of 30,547 traffic accidents involving pedestrians. The second most frequent pedestrian collision partners are bicycles (13%) [2].

The national accident statistics in Germany (free annual reports) do not reveal the exact situation of conflict (detailed accident type code) that lead to accidents between cars and pedestrians. However, a number of states of Germany (states distributed over the country) document those accidents with the three-digit type of accident. For the purpose of this accident research, these data were pooled from six states and analyzed. This data set covers 42% of all observed fatal crashes involving passenger cars and pedestrians (max. two parties) in Germany and is assumed to be representative. In order to obtain the largest possible data set and to even out annual fluctuations, a period of three consecutive years (2008 to 2010) was chosen ($n_{fatal} = 399$; $n_{serious} = 6{,}875$; $n_{slight} = 21{,}751$).
The analysis performed focused on seriously injured and killed pedestrians (impacted by passenger cars) and showed that the major conflicts (crash configurations) with regard to seriously injured people and fatalities can be reduced to the following accident scenarios:

- Pedestrian crossing from near- or off-side without obstruction,
- Pedestrian crossing from near-side behind an obstruction and
- Pedestrian goes along the road without obstruction.

In addition to these scenarios, further scenarios were identified in addition to the preliminary accident scenarios:

- Darkness in scenarios 3 and 4
- Scenario 8 ‘Crossing before or after junctions’
- Scenario 9 ‘Reversing’

The accident scenario 8 (pedestrian crossing directly before or after an intersection; see Figure 2) was separately handled within the German analysis. It is believed that this accident scenario 8 shows a special traffic situation with generally a high number of objects around (vehicles, traffic requirements), crowds of people, multiple lanes and maybe constitutes for a most difficult situation for pre-crash safety systems due to the overall environmental complexity.

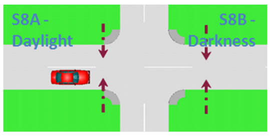


Figure 2: Accident Scenario S8 “Crossing before or after junctions” (identified apart in German accident data)

It has to be noted that accidents allocated to accident scenario 8 were assigned to accident scenarios 1 and 2, for comparison with British data and for later extrapolation since the relevance of this environmental complexity could not be clarified sufficiently yet.

While for adults and elderly people the proportions of the most frequent accident scenarios were similar, the scenario ‘crossing behind an obstruction’ was over-represented for children.
Children were defined up to the age of 11 years inclusively, differently from other commonly used definitions. This selection was made under the assumption that causes of accidents change for older children. Thus, children under the age of 11 years are more frequently obscured by parked cars, while the growth in size changes significantly later. It appears that children frequently cross from the nearside or offside of the road (mostly straight road layout) in daylight (accident scenarios 1 and 2) and thereby be involved in serious accidents (31% of seriously injured and 50% of killed children, see [5]). Further, children cross the road from the nearside, so are particularly common obstacles (e.g. parked vehicles) in the field of view of the car driver (accident scenario 5; 22% of seriously injured and 14% of killed children, see [5]).

Further, it is evident that car-to-pedestrian crashes during ‘dark’ light conditions led to more serious injuries or even the death of pedestrians compared to ‘day’ light conditions.

Results Great Britain

The STATS19 analyses were used to identify common accident scenarios of car-to-pedestrian crashes (here 'car' is referred to passenger cars as well as taxis) and appropriate weighting factors for them. The analysis involved identifying all pedestrian casualties in STATS19; identifying the target population, i.e. pedestrian casualties impacted by the front of a car or taxi and the examining of characteristics of the target population; in particular to determine the proportion injured in each of the preliminary accident scenarios defined.

In total, between 2008 and 2010, 12% of casualties in Great Britain were recorded as pedestrians. Pedestrians accounted for the second largest casualty group after car occupant casualties (64%). Pedestrian casualties recorded as being hit by a car or taxi, where the first point of contact on the associated vehicle was the front, were selected as being members of the target population (46% of the pedestrian casualties). A secondary filter was then applied to remove casualties hit by stationary or reversing vehicles, as these situations were deemed to be inappropriate for this analysis. The final target population consisted of 36,678 pedestrian casualties (n_{fatal} = 803; $n_{serious}$ = 8,169; n_{slight} = 27,706). Pedestrian casualties impacted by the front of a car (or taxi) were defined as members of the target population for this work.

Figure 3 displays the proportion of casualties in each injury severity by age group. It should be noted that the age groups defined are not equal in size; 32% of pedestrian casualties were aged 25-59 years, 21% were aged 16-24, 15% were aged 12-15 and 20% were under 11. The combined older age groups (60-69 and 70 and over) only accounted for 12% of pedestrian casualties. Age was unrecorded for 817 casualties and as a result, these have been excluded from this analysis.

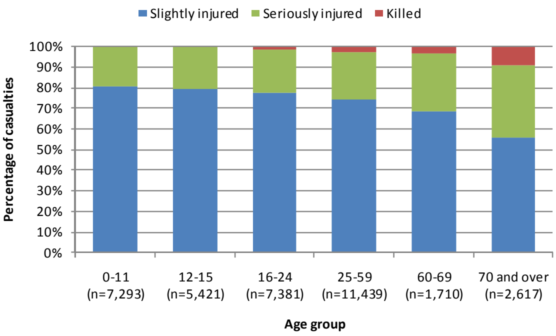


Figure 3: Proportion of pedestrian casualties in each severity by age group, 2008 – 2010, GB

A higher proportion of pedestrian casualties in the older age groups were killed or seriously injured when compared to those in the younger categories. Pedestrians aged 70 and over recorded the highest percentage of casualties killed or seriously injured with 44% falling into these two categories.

Pedestrian casualties are more common on urban than rural roads; 88% of casualties in the target population were recorded in urban areas. However, pedestrians were more severely injured on rural roads than urban; 33% were killed or seriously injured compared to just 23% on urban roads. Pedestrians are rarely injured on motorways (there were only 68 in the target population). However, 74% of these were killed or seriously injured.

Summarised:

- 24% of casualties in the target populations were killed or seriously injured (larger in the older age groups);
- 88% of casualties were injured in urban areas;
- The most common junction characteristics included 'not at within 20 m of junction' (43%), 'T or staggered junction' (36%) & 'crossroads' (10%);
- The most common vehicle manoeuvre was 'going ahead other' (68%);
- The most common pedestrian movements were 'crossing from nearside' (31%), 'in carriageway standing or playing' (19%), 'crossing from offside' (16%);
- A substantial proportion of casualties were impacted when 'crossing on pedestrian crossing facility' (30%);
- A significant proportion of accidents had the contributory factor 'impaired by alcohol' assigned to the pedestrian (10-20% depending on injury severity).

It should be noted that obscuration in STATS19 only includes pedestrians masked by a parked or stationary vehicle. Pedestrians masked by other objects such as street furniture are classified as no obstruction.

Pedestrian speed

Estimating the speed of the pedestrian is more difficult compared to reconstruct a vehicle's speed and can usually not be derived from evidence at the scene of the collision. However, there are various other sources of pedestrian speed data for use in accident reconstruction. These often present detailed walking and running speed data broken down by age and gender. Within the AsPeCSS project reasonable approximations for pedestrian walking and running speeds were derived from a literature review[5] and are shown in Table 4. They may also be suitable for use in pedestrian test scenarios. The same speed is proposed for adults and children (as well as males and females) for simplicity.

Table 4: Pedestrian speeds as used in AsPeCSS

Speed	Adults and children (m/s)	Elderly (m/s)
Walking	1.4 (≈ 5 km/h)	1.2 (≈ 4 km/h)
Running	2.8 (≈ 10 km/h)	2.0 (≈ 7 km/h)

Accidents during 'dark' light conditions

Figure 4 shows the proportion of killed or seriously injured (KSI) pedestrian casualties by light condition in the STATS19 database from years 2008-2010. In the target population, 24,643 (67%) KSI pedestrian casualties were injured in daylight and 29% in darkness with street lights. However, a higher proportion of KSI pedestrian casualties were injured at night on roads where there were no street lights or they were unlit than any other light condition.

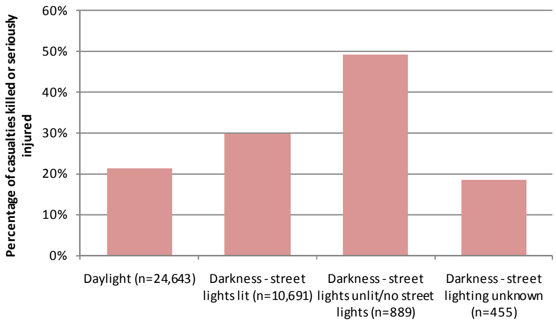


Figure 4: Proportion of KSI pedestrian casualties by light condition, 2008 – 2010, GB

From this and the German accident analysis 'dark' light conditions were identified as a central contributing factor to severe injury outcomes of car-to-pedestrian crashes, especially with regard to pedestrian fatalities – 83% of all pedestrian fatalities in the British and German datasets resulting from accidents between a passenger car and a pedestrian were assigned to the AsPeCSS final accident scenarios, and on average 58% of these occurred during 'dark' light conditions (see Table 8).
The available national accident data from Great Britain and Germany were used to generate an overview of the importance of the 'dark' light condition (including the average of both countries) and are shown for killed and seriously injured (KSI) pedestrian casualties in Table 7 und for fatally injured pedestrian casualties in Table 8. For each country and for the average values the three most frequent accident scenarios are marked in bold. With regard to KSI, on average 25% of car-to-pedestrian crashes were assigned to scenario 1, 20% to scenario 2 and 15% to scenario 7, whereby 'dark' light conditions prevailed in accident scenario 2. With regard to fatalities, on average 30% of car-to-pedestrian crashes were assigned to scenario 2, 23% to scenario 1 and 19% to scenario 7. The 'dark' light condition stands out in terms of pedestrian fatalities as can be seen in the percentages of Table 8. The rate of accidents in 'dark' light conditions accounts for 65% to scenario 1, for 77% to scenario 2 and for 74% to scenario 7.

The analysis above shows that often collisions with a car in dark light conditions end up with serious injuries or death of the pedestrian. Figure 5 shows randomly chosen accident scenes at night from GIDAS. Since a majority of accidents occur in urban areas, there is almost never complete darkness, but always a diffuse illumination by streetlights, traffic lights, street furniture or similar reflections on the wet roadway and / or bright lights from the headlamps. These driver demanding light conditions often occur combined with obstructions and thus lead to a more complex situation.

Man (32) crosses from near-side – MAIS 4

Man (78) crosses from near-side – MAIS 3

Woman (51) crosses from near-side – MAIS 3

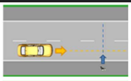
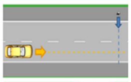
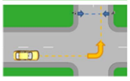
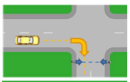
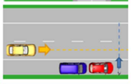
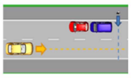
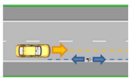
Figure 5: GIDAS examples of car-to-pedestrian collisions on German roads at night with glare, rain, reflections and obstructions

ASPECSS ACCIDENT SCENARIOS

Overview

To take results of previous projects into account, available literature was reviewed and was summarised into preliminary accident scenarios for AsPeCSS (see above). Though the preliminary accident scenarios were largely confirmed by current analyses of German and British data, the accident scenario 3B 'Crossing at junction, near- or off-side, vehicle turning across traffic, dark' and accident scenario 4B 'Crossing at junction, near- or off-side, vehicle not turning across traffic, dark' were added to the final list of Accident Scenarios for AsPeCSS, see Table 5. Accident scenario categories 'Reversing' and 'Parking' were excluded due to their small relevance regarding the forward-looking systems addressed within AsPeCSS.

Table 5: AsPeCSS Accident Scenarios

Drawing	ID	Accident Scenario Description
	1 A/B	Crossing straight road, nearside, no obstruction, day / dark
	2 A/B	Crossing straight road, offside, no obstruction, day / dark
	3 A/B	Crossing at junction, near- or offside, vehicle turning across traffic, day / dark
	4 A/B	Crossing at junction, near- or offside, vehicle not turning across traffic, day / dark
	5 A/B	Crossing straight road, nearside, obstruction, day / dark
	6 A/B	Crossing straight road, offside, obstruction, day / dark
	7 A/B	Along straight road, no obstruction, day / dark

Relevance

The seven preliminary accident scenarios were confirmed to be relevant for Great Britain and Germany and weighting factors obtained. In view of these factors accident scenarios 3 and 4 were joined together. The final AsPeCSS accident scenarios with weighting factors for all pedestrian casualties are given for GB and Germany in Table 6. Highest weights were assigned to scenarios 1 (23%) and 2 (16%), followed by scenario 7 (13%).

Table 6: AsPeCSS Accident Scenarios of car-to-pedestrian crashes in day and dark light conditions (averaged national accident data from GB and Germany of years 2008-2010 for all pedestrian casualties)

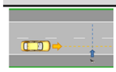
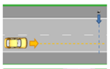
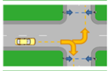
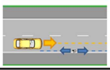
Accident Scenarios	Description	Light condition	All pedestrian casualties GB	Germany	Average
	Crossing a straight road from near-side; No obstruction	All (day/dark)	26 (18/8)	19 (13/6)	23 (16/7)
	Crossing a straight road from off-side; No obstruction	All (day/dark)	13 (8/5)	18 (10/8)	16 (9/7)
	Crossing at a junction from the near- or off-side with vehicle turning or not across traffic	All (day/dark)	6 (6/0)	7 (3/4)	6 (4/2)
	Crossing a straight road from near-side; With obstruction	All (day/dark)	5 (4/1)	7 (6/1)	4 (3/1)
	Crossing a straight road from off-side; With obstruction	All (day/dark)	7 (5/2)	5 (4/1)	8 (6/2)
	Along the carriageway on a straight road; No obstruction	All (day/dark)	22 (15/7)	7 (4/3)	13 (9/4)
	TOTAL	All (day/dark)	79 (56/23)	63 (40/23)	70 (47/23)

Figure 6 shows the weights of the final AsPeCSS accident scenarios (car-to-pedestrian crashes) focusing on killed and seriously injured (KSI) pedestrians using national data from GB and Germany. Highest weights were assigned to scenario 1 (25%; crossing straight road, nearside, no obstruction), followed by scenario 2 (20%; crossing straight road, offside, no obstruction), others (16%) and scenario 7 (15%, along straight road, no obstruction).

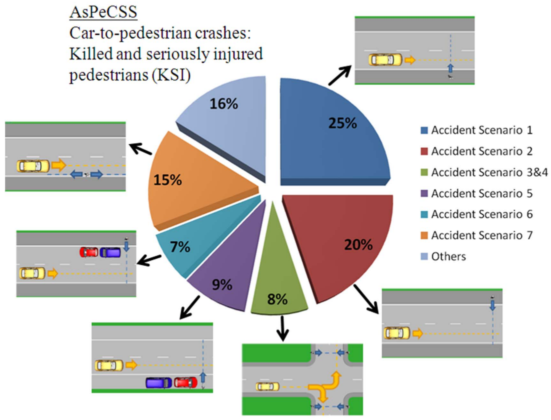


Figure 6: AsPeCSS Accident Scenarios – Overview of killed and seriously injured (KSI) pedestrians in crashes with cars

Figure 7 shows the weights of the accident scenarios (car-to-pedestrian crashes) limited to killed pedestrians using national data from GB and Germany. Highest weights were assigned to scenario 2 (30%; crossing straight road, offside, no obstruction), followed by scenario 1 (23%; crossing straight road, nearside, no obstruction), scenario 7 (19%, along straight road, no obstruction) and others (17%).

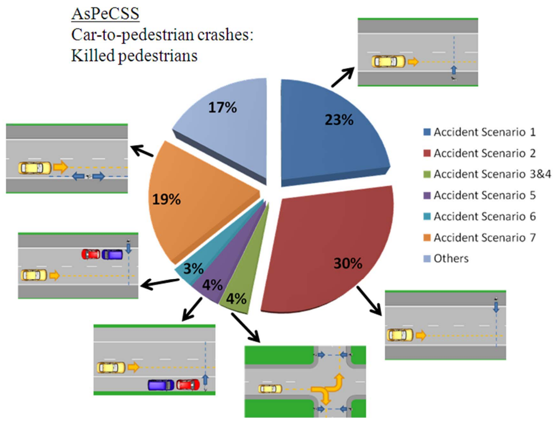


Figure 7: AsPeCSS Accident Scenarios – Overview of killed pedestrians in crashes with cars

In summary, accident scenarios 1, 2 and 7 were found as the three highest weighted scenarios for car-to-pedestrian crash configurations (sum of weights concerning KSI is 60% and concerning fatalities is 72%) that may potentially be addressed by forward-looking integrated pedestrian safety systems. However, accident scenarios 3&4, 5 and 6 (KSI: 24%, Fatalities: 11%) also have a significant weighting as regards future active pedestrian protection systems.

CONCLUSIONS OF ACCIDENT DATA ANALYSIS

There were missing data in all of accident data sources (e.g. total numbers of casualties or vehicle speeds). Thus, a combination of sources and information was used and analysed under consideration of the particularities existing in the countries. However, some general observations could be made.

Similarities within all accident data sources regarding car-to-pedestrian crashes:

- Higher proportion of car-to-pedestrian crashes in urban areas, but higher injury severity on rural roads
- Elderly recorded the highest percentage of casualties killed or seriously injured
- Higher proportion of pedestrian casualties killed or seriously injured when hit by a car in dark light conditions
- Winter months November, December and January show higher number of car-to-pedestrian crashes compared to other months

Differences / deviations within all accident data sources regarding car-to-pedestrian crashes:

- Proportion of pedestrian casualties in crashes with a car (GB: 46% (car front crashes only), GER: 60%) of all crashes with pedestrians.
- Recognition of obstructions (i.e. in the GB 'obscuration' only includes pedestrians masked by a parked or stationary vehicle but other contributors are possible such as clutter close to pedestrian crossings).

For the comparison of KSI (killed and seriously injured) cases (MAIS2+) 84% of GB data and 83% of German data were included. With regard to fatalities 78% of GB data and 87% of German data were included. Remaining percentages include other car-to-pedestrian crash configurations, such as while parking or reversing.

Furthermore, some intersection issues identified in the German data analysis were declared as accident scenario 8 (crossing before or after a junction). In the British data analysis, this accident scenario 8 is included in accident scenarios 1 and 2 and could be seen as subgroups of these. Because it was not sure what the sensitivity of pre-crash safety systems is to the environmental complexity identified in this accident scenario, it was decided, for the time being, that this accident scenario should not be included in the AsPeCSS scenarios and that the related cases from the German data analysis should be assigned to accident scenarios 1 and 2.

Comparison of distribution of casualties by KSI (see Table 7) shows that accident scenarios 1, 2 and 7 are most frequent for both GB and Germany. Significant differences between countries can be seen in accident scenarios 2 and 7 as well as a significant proportion of KSI in dark lighting conditions.

Comparison of distribution of casualties by fatality (see Table 8) shows that accident scenarios 1, 2 and 7 are again the most frequent for both GB and Germany. Significant differences can be seen in accident scenarios 2 and 7 as well as a high share of fatalities during darkness.

Comparison of distribution of all casualties (see Table 6) shows that accident scenarios 1 and 2 are the most frequent for both GB and Germany followed by accident scenario 7 for GB and accident scenarios 3, 4 and 7 (same value each) for Germany, respectively. Significant differences can be seen in accident scenarios 1 and 7 as well as a high share of fatalities during darkness. It has to be noted that 27% of all pedestrian casualties within the German dataset could not be assigned to one of the seven AsPeCSS' accident scenarios.

Compared in total, German data show major issues when a pedestrian crosses a road from off-side during dark light conditions without contributing view obstructions (accident scenario 2). In contrast, GB data show major issues when a pedestrian goes along the carriageway without contributing view obstructions (accident scenario 7).

The seven preliminary accident scenarios were confirmed to be relevant for Great Britain and Germany and weighting factors were obtained. In view of these factors accident scenarios 3 and 4 were joined together. The final AsPeCSS accident scenarios with weighting factors were calculated for all pedestrian casualties for GB and Germany. Hereby, highest weights were assigned to scenarios 1 (23%) and 2 (16%), followed by scenario 7 (13%).

Table 7: AsPeCSS' Accident Scenarios of car-to-pedestrian crashes in day and dark light conditions (national accident data from GB and Germany of years 2008-2010 regarding killed and seriously injured (KSI) pedestrians)

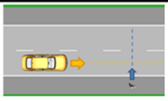
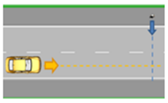
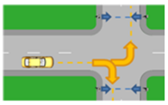
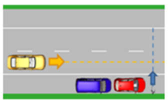
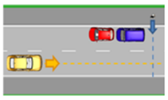
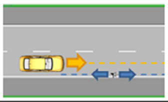
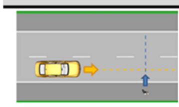
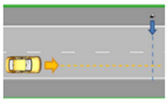
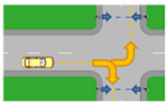
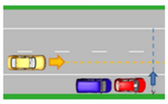
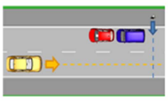
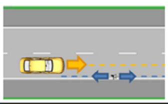
Accident Scenarios	ID	Description	Light condition	Killed and Seriously Injured (KSI) GB	Germany	Average
	1	Crossing a straight road from near-side; No obstruction	All (day/dark)	**27 (16/11)**	**24 (14/10)**	**25 (15/10)**
	2	Crossing a straight road from off-side; No obstruction	All (day/dark)	**16 (8/8)**	**24 (11/13)**	**20 (8/12)**
	3, 4	Crossing at a junction from the near- or off-side with vehicle turning or not across traffic	All (day/dark)	4 (4/0)	**12 (6/6)**	8 (5/3)
	5	Crossing a straight road from near-side; With obstruction	All (day/dark)	6 (4/2)	11 (9/2)	9 (7/2)
	6	Crossing a straight road from off-side; With obstruction	All (day/dark)	7 (5/2)	7 (5/2)	7 (5/2)
	7	Along the carriageway on a straight road; No obstruction	All (day/dark)	**24 (14/10)**	5 (2/3)	**15 (8/7)**
		TOTAL	All (day/dark)	84 (51/33)	83 (47/36)	84 (48/36)

Table 8: AsPeCSS' Accident Scenarios of car-to-pedestrian crashes in day and dark light conditions (national accident data from GB and Germany of years 2008-2010 regarding killed pedestrians)

Accident Scenarios	ID	Description	Light condition	Fatalities GB	Germany	Average
	1	Crossing a straight road from near-side; No obstruction	All (day/dark)	**23 (8/15)**	**23 (8/15)**	**23 (8/15)**
	2	Crossing a straight road from off-side; No obstruction	All (day/dark)	**20 (7/13)**	**40 (8/32)**	**30 (7/23)**
	3, 4	Crossing at a junction from the near- or off-side with vehicle turning or not across traffic	All (day/dark)	2 (2/0)	5 (3/2)	4 (3/1)
	5	Crossing a straight road from near-side; With obstruction	All (day/dark)	2 (1/1)	6 (3/3)	4 (1/3)
	6	Crossing a straight road from off-side; With obstruction	All (day/dark)	4 (2/2)	3 (1/2)	3 (1/2)
	7	Along the carriageway on a straight road; No obstruction	All (day/dark)	**27 (9/18)**	**11 (2/9)**	**19 (5/14)**
		TOTAL	All (day/dark)	78 (29/49)	88 (25/63)	83 (25/58)

Driving and Collision Speeds

National accident databases usually do not provide sufficient data in terms of driving and/or collision speed of vehicles. Though in STATS19 (GB) information about the speed zone is given for each accident, this is of limited use in determining the actual driving speed of the vehicle. Thus, the German in-depth accident study GIDAS (years 2000-2011) was used to determine vehicle speed data in car-to-pedestrian crashes.
Note: the driving speed or initial velocity is defined as the speed in km/h before a critical situation was recognised. The collision speed is the speed of the vehicle in km/h at the time of collision. The speed change (delta V) is the difference between a car's driving and collision speed in the relevant impact.

The initial GIDAS dataset used contained 2,113 pedestrian casualties. To ensure a comparable dataset, crashes with known vehicle speeds (e.g. by reconstruction) were selected. Thus, the GIDAS analysis used the following data query:

- Car-to-pedestrian crash
- All injury severities (pedestrians)
- Known driving speeds (> 0 km/h)
- Known collision speeds

This resulted in a dataset containing 1,432 pedestrian casualties of all injury severities. Figure 8 shows boxplots of the passenger car driving speeds for each accident scenario and for all crashes. The median driving speeds differ widely from 47 km/h (scenario 7) to 20 km/h (scenario 4).
Figure 9 shows boxplots of the passenger car collision speeds for each accident scenario and for all crashes. The median collision speeds differ again widely from 42 km/h (scenario 7) to 16 km/h (scenario 4).

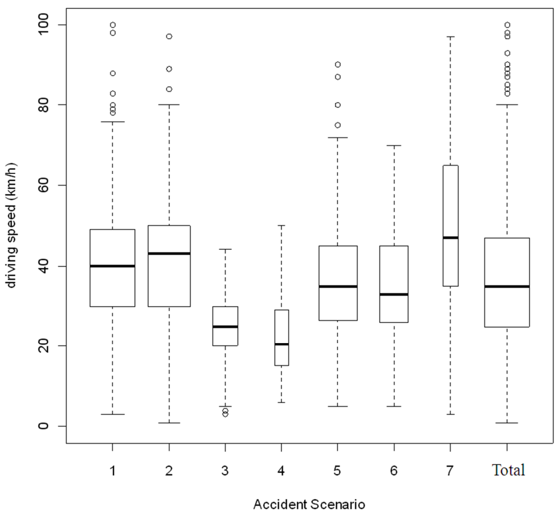


Figure 8: Boxplots of known driving speeds (>0 km/h) for each accident scenario and all accidents

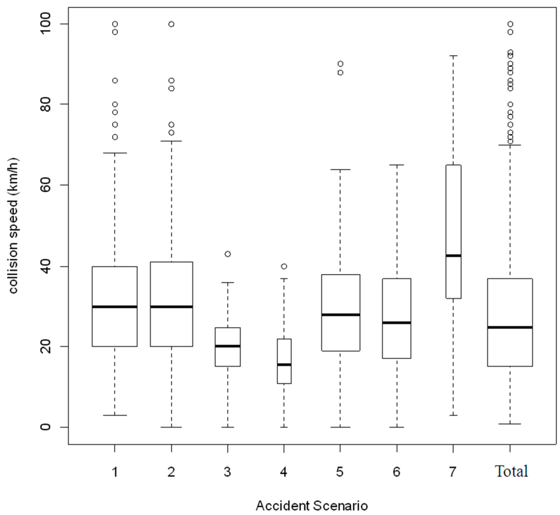


Figure 9: Boxplots of known collision speeds for each accident scenario and all accidents

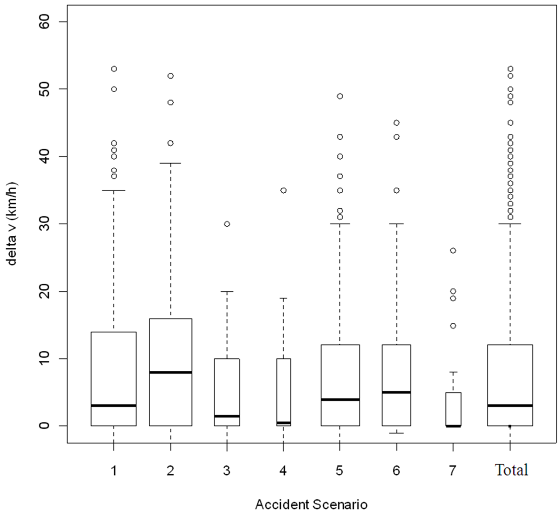


Figure 10: Boxplots of known speed change (delta V) for each accident scenario and all accidents

Figure 10 shows the speed changes that occurred in each individual crash per accident scenario and for all accidents. All medians of these delta V values are below 10 km/h and around 4-5 km/h.

The calculated speed changes (delta V) for each accident scenario could be taken as a general basis for the estimation of braking behaviour within each accident scenario. Scenarios 3 and 4 (vehicle turning) showed together with scenario 7 smallest differences (compared to other scenarios) between driving and impact speeds which implies that there was no braking by the driver in most cases. However, this was strongly linked to the overall lower speeds. Further, it is interesting to note that the speed changes in scenario 2 (crossing pedestrian from offside without obstruction) were slightly higher than in scenario 1 (crossing pedestrian from nearside without obstruction). This might indicate the earlier recognition of the pedestrian crossing from offside. The very low speed changes in scenario 7 (walking along) indicate that the driver did hardly ever reacted to the present of the pedestrian. This was maybe due to late recognition, an incorrect estimation of the pedestrians' behaviour or the absence of crash avoidance actions by the pedestrian.

In [5] another analysis was performed by dividing all pedestrian injuries into groups 'all injury severities' (MAIS > 0) and 'high injury severity' (MAIS 2-6). Conclusions drawn from that analysis were:

- On average the driving and impact speeds were higher (~10 km/h) when focussing on high injury severity pedestrian casualties.
- Highest driving and impact speeds were seen for the 95th percentile in scenario 7 (pedestrian walking along the road), followed by scenarios 1 and 2 (both crossing pedestrian without obstruction), followed by scenarios 5 and 6 (both crossing pedestrian with obstruction) and scenarios 3 and 4 (vehicle turning).

Lateral distance

Within AsPeCSS an accident data (GIDAS) study was performed to quantify the distances (here referred as 'lateral distances') between a subject vehicle and an obstruction in car-to-pedestrian crashes. Here, the accident scenario 'Child runs onto the road from near-side from behind an obstruction' was selected (see examples in Figure 11), since there is a lack of information with regard to the lateral distance.

The case-by-case analysis focused on photos, evidences for distances, information about vehicle and tram track widths, accident scene drawings true to scale etc. Finally, the crashes were categorised to three quality levels (poor, moderate and good) regarding the ability to provide information about the lateral distance. Hereby, 'good quality' is referred to an accident record that enables a realistic understanding of the distance between the car and the obstruction. The analysis classified 75 relevant crashes into the three quality levels (n_{good} = 26, $n_{moderate}$ = 34, n_{poor} = 10, n_{NA} = 5); whereby cases assigned to the moderate and good quality were used for the definition of the lateral distances. Figure 12 shows the results of the lateral distance analysis, whereby the median was 100 cm.

In conclusion, 100 cm are recommended as lateral distance between the exterior of the subject vehicle (excluding side mirrors) and the object causing obstruction (e.g. parked car or bus) [5].

Figure 11: Case examples ('good quality') for the lateral distance analysis using GIDAS (white arrows indicate childs' moving direction)

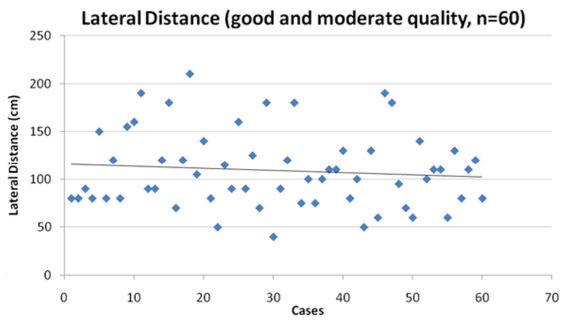


Figure 12: Results of GIDAS analysis of the lateral distance between the exterior of the subject vehicle and the 'obstruction causing object' in accident scenario 'Child runs onto the road from near-side from behind an obstruction'

TEST SCENARIOS

Methodology for definition of test scenarios

Test scenarios should represent the accident situation and thus real conditions. But rebuilding those scenarios in the laboratory or on a test track is very complex, if all characteristics would be reproduced in detail. It still has to be investigated which set of characteristics may be omitted as long as these do not influence the performance of any AEB (Automatic Emergency Braking) system.
The methodology to generate test scenarios used within ASPECSS was composed of two steps:

Firstly, a simplified model for the accident kinematics was generated. This model was based on the fact that if there was a pedestrian accident, then the pedestrian and vehicle must have shared one point in space for one specific time, i.e. the impact. Then assuming speeds for the pedestrian and the vehicle, assuming an angle between their paths and use these assumptions to derive their motion in the pre-crash phase. This simplified model is completely independent from current or future performance of AEB systems.

Next, a simplified model for the performance of AEB systems was derived based on the sequence detection of pedestrian – decision for braking – increase of brake pressure – full braking. Assume a decision logic for the brake system based on pedestrian dynamics and current product liability laws. Assume characteristics of current and future brake systems and calculate the performance.
With the knowledge defined in these two steps, relevant parameters can be isolated. This helps defining a very limited set of test scenarios that still represent a large number of accidents.

Selection Criteria

Test scenarios are an abstraction of key characteristics of accident scenarios that can be reproduced in a test environment. The choice of test scenarios was driven by the following factors:

- Should reflect real-world conditions as accurately as possible.
- Should include a variety of different accident scenarios, not necessarily accidents with highest frequency only (also in order to avoid constraining system design).
- Consideration of current system capabilities (different technologies) and testing feasibilities (i.e. R&R, lighting condition)
- Consideration of driver / sensor situation perception

Parameters for AEB-Pedestrian functionality

For automatic emergency braking, the pedestrian needs to be detected as a relevant target, and after that the brake force needs to be increased. This short functional description already contains the most relevant parameters which can be used to define test scenarios: The time needed for detection of the pedestrian, and the time needed to increase the brake force from no to full braking. To avoid false activations, in general AEB functions will try to brake as late as possible. This reduces the relevant pre-crash time to the time needed to come to a full stop (depends on the speed but in general is < 1 s) and the detection time before that (< 1 s).
This means that all scenarios where the pedestrian is visible around 2 s before impact will very likely show the same performance – there is no need to have test scenarios with larger initial Time-To-Collision (TTC) values.
On the other hand, there will be a significant drop in AEB performance when the pedestrian is visible later than around 2 s before the impact.
This threshold of e.g. 2 s corresponds to a walking distance of around 3 m for the walking adult (5 km/h), and 1.7 m for the walking elderly (3 km/h). System-wise, there are two different types of scenarios: those where the pedestrian was visible 3 m laterally from the impact point (1.7 m for the walking elderly), and those where the pedestrian was visible laterally closer to the impact point.
In other words: all accident scenarios with the pedestrian and vehicle travelling at constant speeds and constant paths can be classified either as obstructed scenarios or as unobstructed scenarios. And from a system symmetrical performance point of view, an off-side obstructed scenario is same as a near-side scenario. The term off-side implies that the pedestrian having an accident, comes from the far side of the road from behind the other lane going towards its impact point, which will be farther than the 3 m from the impact point.

Besides these most contributing parameters, other relevant parameters are environmental conditions as well as the trajectory of the vehicle. For instance the environmental conditions, in particular the lighting, are expected to affect the performance of most AEB-Pedestrian (AEB-P) systems significantly. And, there are a few accident scenarios where the vehicle does not travel on a constant course but performs a turn in the pre-crash phase. The AEB-P performance in these situations may or may not be comparable.

Base and Enhanced Test Scenarios

The test scenarios defined by AsPeCSS follow these considerations: Test Scenario (TS) 1 features a running child from behind an obstruction at 1 m lateral distance to the vehicle path and is an ‘obstruction’ type scenario, while TS2 and TS3 are ‘non-obstruction’ type scenarios during daytime. TS2 and TS3 will also be tested during night conditions once available. The classification of ‘child’, ‘adult’ and ‘elderly’ to the test scenarios was made based on the related assignment of personal data to the accident scenarios (see [5]) and mirrors the size and walking speed (see Table 4) of pedestrians.
Turning maneuvers will be covered by a specific test scenario as well as crossing before or after complex intersections and scenarios where the pedestrian is walking along a road on the near-side in the vehicle driving direction. This latter scenario

is technically an ‘unobstructed’-type scenario with a lateral pedestrian speed of zero, but the longitudinal speed of the pedestrian is relevant for detectability by some kinds of sensors, even if it is low.

As a first step and since testing tools and set-ups are not yet available to address crossing situations and conditions under darkness, Base Test Scenarios have been developed to be testable within the next two years. In addition, Enhanced Test Scenarios will be developed in a later phase.
Further, the AsPeCSS project aims to at least investigate the reaction of AEB-P systems in cases where e.g. the pedestrian stops its movement and thus avoids the collision (‘tests with stopping pedestrian avoiding the crash’). Test scenarios for this will also be developed in a further stage of the project. See Table 9 for a full list of the scenarios.

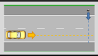
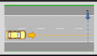
Table 9: AsPeCSS Test Scenarios

ID	Test Scenario Description
	Base Test Scenarios
TS1	Child crosses from near-side behind an obstruction
TS2a	Elderly crosses from off-side (unobstructed)
TS3a	Adult crosses from off-side (unobstructed)
	Enhanced Test Scenarios (to be decided)
TS2b	Elderly crosses from off-side in twilight
TS3b	Adult crosses from off-side in darkness
TSx	Turning manoeuvre
TSx	Pedestrian goes along the road (maybe with bend)
TSx	Crossing before or after a complex intersection
	Tests with stopping pedestrian avoiding the crash

Mapping Accident Scenarios to Test Scenarios

Major differences between the test scenarios are the walking speed of the pedestrian and the obstruction status (with or without). Based on these factors, one test scenario can be associated with a number of accident scenarios. The mapping relationship between accident and base test scenarios is shown in Table 10 where the averaged weight for pedestrian fatalities of crashes with cars is added for daylight and dark light conditions. Basically, TS1 is assumed to address accident scenario 5 and thus a system highly demanding scenario. Further, TS2 and TS3 are assumed to address accident scenarios 1, 2, 3&4 and 6. Question marks are included in Table 10 in fields where it is believed that pedestrian pre-crash sensing systems may cover potentially (ranging from partial to full) the accident scenarios (e.g. in dark light conditions depending on the kind of sensor technology and/or system evaluation characteristics). This mapping of scenarios is currently ongoing work within AsPeCSS.

Table 10: Mapping from Accident Scenarios to Base Test Scenarios including light conditions (‘?’ indicates partial to full addressability)

ID	Accident Scenario Description	Fatalities (%) ☀/☾			
1 A/B	Crossing a straight road from near-side; No obstruction	23 (8/15)		☀ ☾?	☀ ☾?
2 A/B	Crossing a straight road from off-side; No obstruction	30 (7/23)		☀ ☾?	☀ ☾?
3 A/B 4 A/B	Crossing at a junction from the near- or off-side with vehicle turning or not across traffic	4 (3/1)		☀? ☾?	☀? ☾?
5 A/B	Crossing a straight road from near-side; With obstruction	4 (1/3)	☀ ☾?		
6 A/B	Crossing a straight road from off-side; With obstruction	3 (1/2)		☀ ☾?	☀ ☾?
7 A/B	Along the carriageway on a straight road; No obstruction	19 (5/14)			

Test Scenario Parameters

Driving and collision speeds have been analysed using the in-depth accident database GIDAS to support the development of test scenarios with realistic speed ranges. Figure 13 and Figure 14 show speeds of passenger cars involved in crashes with pedestrians according to the specifications for the Base Test Scenarios defined, subject to all injury severities and high injury severity (MAIS 2+), respectively. In all datasets used (designated to the three Base Test Scenarios) higher speeds were present in case of MAIS 2+ injured pedestrians. Speeds are generally lower for TS1 than for TS2 and TS3 which is directly connected with the location of usual occurrence - urban roads. Because of these data and current testing feasibilities (mainly due to the pedestrian dummy robustness) the upper testing speed limit was set to 60 km/h. Further, it was recommended to set the lower testing speed limit not below 10 km/h.

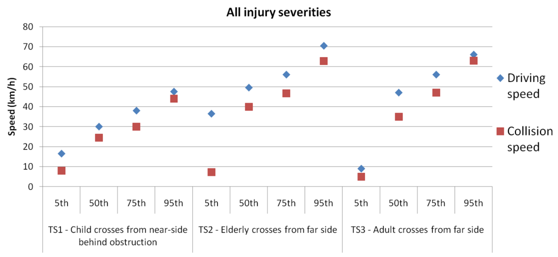


Figure 13: Vehicle speeds by analysis of GIDAS data (all pedestrian injury severities, not weighted, years 2000-2011)

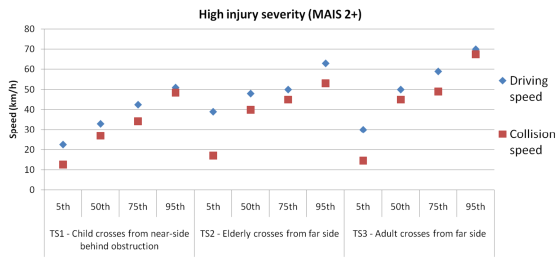


Figure 14: Vehicle speeds by analysis of GIDAS data (high pedestrian injury severity by MAIS 2+, not weighted, years 2000-2011)

The AsPeCSS project also defines varying impact positions of the pedestrian on the vehicle front: 50% (= center impact) for TS2 and TS3 and 25% / 75% (on vehicle front, approx. 40 cm from the left and right vehicle side) for TS1. A detailed explanation of impact position and its effect on the expected system performance can be found in [5], and [8].

WEIGHTING FACTORS FOR EUROPE

Approach

Accident scenario weighting factors derived from national accident data from Germany and the GB were used to extrapolate to the EU-27 countries. In AsPeCSS, detailed data related to crashes with pedestrians was available from GB, Germany, partly from France and the Netherlands but not as a whole for the EU-27. Even the high-level compiled EU accident databases (i.e. CARE, IRTAD) offered little information. Thus, a statistical approach was needed to extrapolate the available data (and proportions) to Europe (EU-27).
The national accident data analysis within [5] and this paper focused on all car-to-pedestrian crashes in Germany and on frontal collision car-to-pedestrian crashes in GB (for the GB analysis it was assumed that lateral collisions with pedestrians should not be included in the target population because the forward looking pedestrian systems would not offer any benefit for them).

Due to several constraints, the post-stratification methods proposed initially could not be applied but the envisaged raking procedure and the Iterative Proportional Fitting (IPF) methods also proposed initially will be considered in a later stage of the AsPeCSS project.
Therefore, a simple approach which averaged the available accident data was chosen to calculate indicative weighting factors for Europe with regard to all seven accident scenarios.

Since the weighting factor analyses to date (see i.e. Table 7 and Table 8) are in relationship to a target population (car-to-pedestrian crashes) within all pedestrian casualties, a re-calculation of the weighting factors was needed (normalization) to provide an overview of the importance of the accident scenarios. That is, based on the analysis of the national accident data within [5] the new proportions of KSI, fatalities and all pedestrian casualties had to be calculated for Germany and GB. These proportions are shown in Table 11. While these percentages are similar for killed pedestrians in Germany (56%) and the GB (55%), the proportions for KSI differ between Germany (66%) and the GB (50%) as well as for all pedestrian casualties between Germany (60%) and the GB (46%).

Table 11: Proportion of seriously injured and/or killed pedestrians and all pedestrian casualties in crashes with a passenger car[2] against all seriously injured and/or killed pedestrians and pedestrian casualties in road traffic for Germany (average from years 2010 and 2011) and Great Britain (average from years 2008 – 2010)

	Germany			Great Britain		
	KSI	Fatalities	All casualties	KSI	Fatalities	All casualties
Proportion of seriously injured and/or killed pedestrians in crashes with a passenger car against all seriously injured and/or killed pedestrians in road traffic	**66%**	**56%**	**60%**	**50%**	**55%**	**46%**

The proportions from Table 11 were now used to calculate the weighting factors for Germany and GB with regard to the AsPeCSS Accident Scenarios.
Finally, the calculated weighting factors from German and GB data were averaged to estimate initial weighting factors in this first phase of the AsPeCSS project. The results are listed in Table 12. No further marginal distributions (i.e. population or vehicle registration numbers) have been considered since their influences were not clarified. From this calculation the conclusion can be derived that the AsPeCSS Accident Scenarios cover nearly half of all killed pedestrians (46%) and nearly half of all seriously injured and killed (KSI) pedestrians (49%) as well as 37% of all pedestrian casualties in Europe.

Table 12: Averaged weighting factors (%) of Accident Scenarios for killed and seriously injured (KSI), Fatalities and all pedestrian casualties of all crashes including pedestrians in GB and Germany

Accident Scenario	KSI	Fatalities	All casualties
1	15%	13%	11%
2	12%	17%	9%
3+4	5%	2%	4%
5	5%	2%	3%
6	4%	2%	3%
7	8%	10%	7%

Finally, the assumption was made, that the weighting factors listed above represent valid proportions for all EU-27 countries. This strong assumption will be checked during further research work, whereby marginal distributions will be derived from EU accident data.

[2] GB data: Frontal passenger car / taxi / hired car collisions with pedestrians

DISCUSSION AND LIMITATIONS

The analysis presented is limited to car-to-pedestrian crashes and hence, the impact of a potential future development of the test scenarios towards passenger car crashes with cyclists has not been considered yet. Due to the limitations in current testing procedures of active safety systems (e.g. 'dark' light conditions), base test scenarios were developed with the intention of adding enhanced test scenarios in future. These will take into account parameters such as turning manoeuvers, complex intersections and environmental conditions such as darkness, if found necessary, i.e. the performance of the system changes significantly with a change in these conditions.

CONCLUSIONS

Within the European FP7 project AsPeCSS different European accident data sources have been used to investigate the causations and backgrounds of road traffic accidents with pedestrians. Analyses of high level national data and in-depth accident data from Germany and Great Britain was used to confirm and refine preliminary accident scenarios identified from other projects such as AEB and vFSS. General observations made included that a higher proportion of pedestrian casualties killed or seriously injured was found when hit by a car in 'dark' lighting conditions. Seven Accident Scenarios were identified (each divided into 'daylight' and 'dark' light conditions) which included the majority of the car-to-pedestrian crash configurations. Accident Scenarios were identified with weighting factors and associated test scenarios were developed to assess the performance of the pre-crash braking component of integrated pedestrian safety systems.

ACKNOWLEDGEMENT

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A METHOD FOR DEVELOPING AEB SYSTEMS BASED ON INTEGRATION OF VIRTUAL AND EXPERIMENTAL TOOLS

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ABSTRACT

This paper proposes an enhanced methodology for AEB system development combining road testing, in-door laboratory testing, hardware-in-loop testing and simulations. The application of the modeling part of methodology is demonstrated using an OEM vehicle system. The physical AEB system is subjected to the AEB City and AEB Inter Urban test series as proposed by Euro NCAP. The test series are executed in a laboratory environment. Simulation models are generated and validated against the experimental data from these test series. System sensitivity is evaluated using a parameter variation study and validated simulation models.

1. INTRODUCTION

Several car manufacturers have introduced autonomous braking systems with the aim of mitigating the effects of accidents or even preventing accidents from occurring. The benefit of these autonomous braking systems to vehicle safety is acknowledged by legislative authorities and consumer bodies, which has led to several initiatives to legislate or reward these new safety technologies. The European Commission is mandating autonomous emergency braking (AEB) systems for commercial vehicles from 2013. Euro NCAP will include AEB systems in their rating system from 2014. Euro NCAP has proposed a standard test protocol representing the most important scenarios for urban (AEB City) and non-urban (AEB Inter-Urban) conditions. However, a wider set of traffic scenarios must be considered during AEB system development to guarantee reliable and robust functioning in real-world traffic. It is too costly and time-consuming to test all these real-world scenarios on a test track or public road. This issue will grow further with the next generation AEB safety that will include vulnerable road user safety (AEB Pedestrian). Reproducible and controlled scenario conditions are essential to achieve complete evaluation during system developments. This paper proposes an enhanced methodology for AEB system development combining road testing, in-door laboratory testing, hardware-in-loop testing and simulations. The paper will provide an overview of the entire development methodology for AEB systems, and will address in more details the role of indoor lab testing and the validation and usage of CAE models.

Section 2 gives an introduction of the simulation environment and a description of the AEB vehicle modeled that is used throughout the study. Next, in section 3, the AEB laboratory experiments used for the system assessment are presented, and the validation of the simulation model is shown. Section 4 presents three parameter variation studies that are executed based on the validated AEB simulation modeled from section 5. Finally, section 6 contains concluding remarks as well as an outlook to future studies.

2. CAE MODEL DESCRIPTION

2.1 PreScan

The CAE tool that is used in the methodology is PreScan software [1]. PreScan is physics-based simulation platform that is used in the automotive industry for development of Advanced Driver Assistance Systems (ADAS) that are based on sensor technologies such as radar, laser/lidar, camera and GPS. PreScan is also used for designing and evaluating vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication applications. PreScan can be used from model-based controller design (MIL) to real-time tests with software-in-the-loop (SIL) and hardware-in-the-loop (HIL) systems. (see Figure 1).

The tool allows to build various traffic scenarios using a database of road sections, infrastructural components (trees, buildings, traffic signs) and road users (cars, trucks, cyclists, pedestrians as well as balloon cars). Weather conditions (rain, snow, fog) and light circumstances can be modeled as well. The vehicle models can be equipped with one or more different sensor types. A Matlab/Simulink interface enables users to design and verify algorithms for data processing, sensor fusion, decision making and control as well as the re-use of existing Simulink models such as vehicle dynamics models. PreScan can be used for model-based controller design (MIL), real-time tests with software-in-the-loop (SIL) and hardware-in-the-loop (HIL) systems [2, 3, 4, 5].

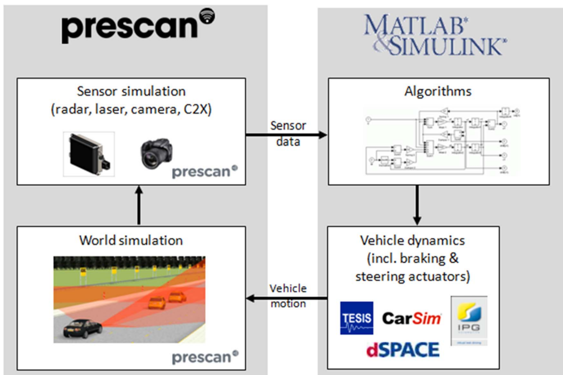


Figure 1. The co-simulation principle of PreScan and Matlab/Simulink

2.2 CAE model of an Autonomous Emergency Braking System (AEBS)

System Description: This paragraph describes the design, usage, and testing of the AEBS model built in PreScan and Simulink. The main principles of the system model (sensoring and system deployment policies) are based on the functionality of the current systems available on the market. The AEB system model uses the information from long-range radar and the host vehicle to identify the potential collision risk with the objects detected by the radars (Figure 2).

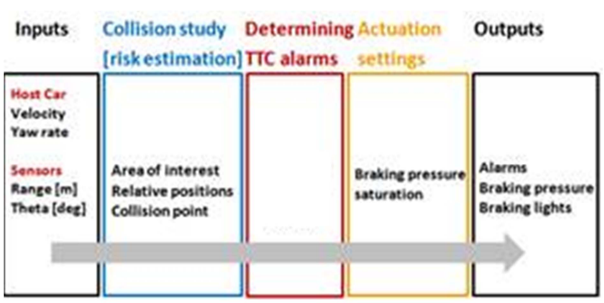


Figure 2. Information and decision flow in the AEBS controller model.

The calculation is based on the information about the area of interest (direction of the car), relative position and direction of the moving or stationary object. Based on this information, the collision point is estimated and object is classified as collidable. The parameter Time To Collision (TTC) is calculated and the controller determines the warning alarms to prompt the driver based on the TTC values and the relative velocity difference between the host vehicle and the target object. The warning is deployed earlier if the relative velocity difference is larger and vice versa. At this point, the system waits for the driver to intervene: either by releasing the accelerator or pressing the brakes.

Based on the driver reaction, appropriate pressure is set in the braking actuation block and the controller output is sent to the actuators: braking system and braking lights. The following steps are taken by the AEBS:

- warns driver to act in order to prevent accident
- intervenes when driver reacts through;
  - Autonomous **partial braking** when driver releases the accelerator
  - Autonomous **full braking** when driver pushes the brakes

System Modeling: Host Car with AEBS: The AEB system model is a Simulink model (available as part of the PreScan software release) that is placed on a PreScan car model, representing a generic passenger car with driving performance typical for mid-class car, and a driver model. The braking model is based on the PreScan internal vehicle dynamics model and it can generate maximum 0.85G of braking deceleration. Figure 3, shows the placement of the radar sensor on the car; lower left bumper.

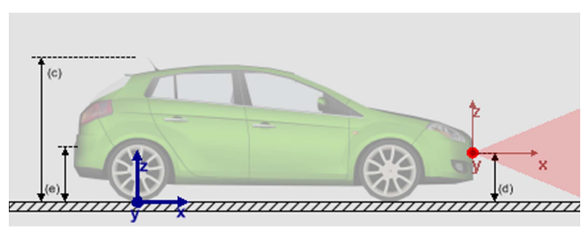


Figure 3. PreScan Model of the car with LRR

The TIS (Technology Independent Sensor) models of sensors available in PreScan database were used to represent the long range radars with the following settings: Long range radar (LRR), 200m range, 10deg FoV.

System Modeling: Driver Model: The modeled AEBS system requires driver intervention for brake deployment. There was a need to model the driver reactions to the warning system for AEB system operation. Estimation of the driver reaction delay to system warning is an active research area [6]. Traditionally the driver reaction time estimation studies have been carried out on driving simulators [7]. In the ASSESS project a similar study was carried out [8] to quantify the driver reaction time on two different simulators. In the aforementioned study, although the experimental designs were based on the same concept, different results were observed, illustrating the difficulty in obtaining robust reaction times to a warning. The study concluded that it is very difficult to robustly define a generic driver reaction that is applicable to a range of different scenarios.

PreScan simulation environment was utilized to estimate the driver reaction times to PreScan warnings for the tested scenarios. A Matlab model for estimating the driver reflexes and response delay times, based on the Driver in the Loop Experiments carried out using Logitech Hardware, was implemented. A total of 11 participants were tested and their response times to driver warning were noted down and used as inputs to the applied driver model. The resulting data are presented in Table 1.

Table1. Resulting average data for human driver reflexes and response delay times

	First Reaction Time: Time to Release Accelerator [s]	Second Reaction Time: Time to Press Brake [s]
Average of 11 participants	0.59	0.11

<u>System Modeling: Target Balloon Car</u>: The target object is a PreScan model of a draft version of the Euro NCAP balloon target cover that is being pulled by a truck. The PreScan driver model controls the trajectory for the truck and consequenly for the target object.

<u>PreScan Scenarios</u>: The pre-crash scenarios considered rear-end collision to vehicles in city and inter-urban surroundings. In each scenario the car is equipped with autonomous emergency braking system model. In Figure 4, the CAE model is shown. The scenario model represents a straight suburban road, side objects, host car and other traffic participants.

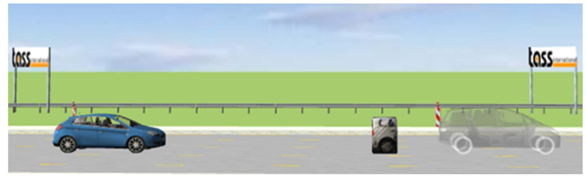


Figure 4. PreScan represented scenario with the vehicle under test and the balloon target.

The modeled test scenarios have been selected to in line with the scenarios for AEB City and Inter-Urban as are currently foreseen in [10, 11] The represented scenarios, Table 2, cover three variations of the basic case Car-to-Car Rear end (CCR) collision;

- Test T1 (CCRm): Approaching a slow moving object
- Test T2 (CCRb): Approaching an object decelerating constantly
- Test T3 (CCRs): Approaching a stationary object

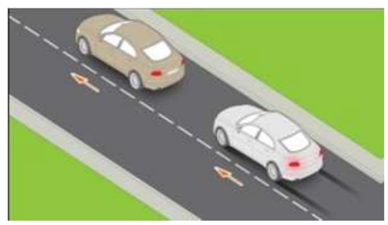


Figure 5a. Slower Lead Vehicle

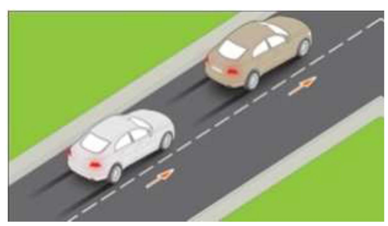


Figure 5b. Lead Vehicle Decelerating

Figure 5c. Lead Vehicle Stopped

Table2. PreScan Represented Scenarios

Scenario	Host Car speed [km/h]	Target Car speed [km/h]	Target Deceleration [m/s]	Initial Distance [m]
Test T1	50-80	20	-	75
Test T2	50	50	-2,-6	12,40
Test T3	10-80	0	-	120

Limitations of the CAE model: An average vehicle has been identified for this study and the standard vehicle dynamics model available in PreScan software has been adopted. The model has the following assumptions;

1. linear suspension model;
2. ideal friction conditions (dry road, new tyres)
3. No Anti-lock braking system;

The controller represents the basic functionality of an AEBS controller. The detailed architecture of the controller might not be a true representation of the advanced functionality of the AEB System of the tested vehicle.

3. MODEL VALIDATION

3.1 Laboratory experiments

The TNO VeHIL laboratory allows for testing an active safety system (sensors, ECU, actuators, HMI and vehicle motion) in controlled and safe laboratory conditions [4, 5]. For the pre-crash evaluation of the AEB system a new setup is used, that has been developed and evaluated in the EU ASSESS project [9]. This is based on movement of a balloon target that can impact the test vehicle in frontal scenarios. In this setup, the moving balloon target is guided by a floor mounted cable system that accurately controls the motion of the target, as shown in Figure 6.

The balloon target (different targets are possible) is accelerated or decelerated in driving direction of the vehicle whit speeds up to 80 kph and with varying overlaps. In a safe, repeatable and non-destructive manner a scenario is evaluated until the actual moment of impact (TTC=0), measuring speed reduction, braking profiles and system timings.

Figure 6. VeHIL setup with PreCrash setup with balloon target

In different recent investigations, most importantly the work done as part of the EC ASSESS project, the VeHIL AEB test method is evaluated. In the ASSESS study the VeHIL Pre-Crash test setup was benchmarked with different scenarios, different AEB vehicle systems, different balloon targets and different outdoor and indoor pre-crash test methods in Europe. The results and conclusions of this work are described in ASSESS [9]. In this paper the earlier ASSESS evaluation work done is extended with a a range of AEB Car to Car Rear scenarios with the Euro NCAP target (Figure 7).

Figure 7. Used balloon target in for lab testing

3.2 Model correlation

The results for the tests represented in PreScan and VeHIL were compared. Table 3 presents the average of the percentage correlation levels for the three type of CCR tests carried out in VeHIL lab and then represented in PreScan, as discussed in section 2.To simplify the analysis, the vehicle was compared for the completely autonomous functionality of the AEB system under discussion;

initiation of the driver warning. Each test was conducted three times to provide input for the repeatability and reproducibility analysis for the VeHIL testing facility.

Scenario	**Warning -** Time To Collision [s] **% Correlation PreScan**
Test_T1	91%
Test_T2	60%
Test_T3	94%
Average:	**81%**

Above table presents the correlation levels between VeHIL and PreScan test results. Tests T1 and T3 show a correlation level of about 90%. Test T2 shows lower levels of correlation due to the simplified braking profile that was adopted for the PreScan simulations of the target car.

4. PARAMETER VARIATION STUDY

A simulation study was conducted to investigate the sensitivity of certain parameters (braking pressure, sensor noise and road curvature) on the performance of the AEB system under test. The primary objective was to demonstrate the application of the aforementioned methodology for developing AEB systems.

4.1 Brake Pressure Variation Study

AEB combines advanced driver assist systems and premium electronic stability control to rapidly decelerate the vehicle with or without driver intervention if a crash is determined to be inevitable. The Brake Pressure Variation (Maximum Applied Deceleration) tests aim to evaluate the effectiveness of the AEBS under different deceleration conditions. The rearward impact scenario is modeled, the car travels at the speeds of 30-100 km/h, the target car moves at a speed of 20 km/h and the braking conditions are varied for each scenario. The AEB system generates a warning at the risk of collision with the slowly moving target vehicle. It is assumed that the driver applies brakes, at which the system applies the maximum possible deceleration (tested variable parameter). The behavior of the host car, if it manages to avoid the collision or not, is noted down for different deceleration conditions for different test speeds for the host car.

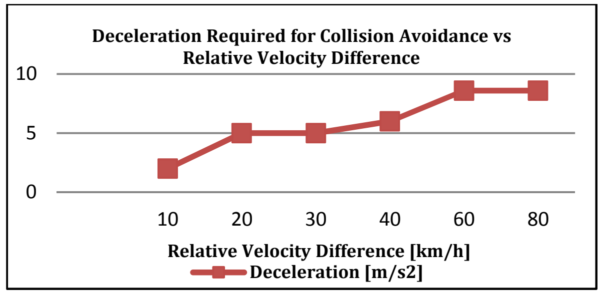


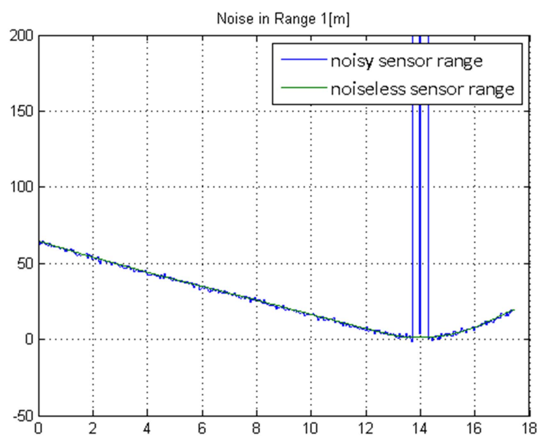
Figure 8. Maximum Deceleration Required for Collision Avoidance vs Relative Velocity Difference

It was observed that for a relative velocity difference of 10 km/h a deceleration of 2 m/s2 was enough to avoid the collision. Similarly, for a relative velocity difference of 40 km/h a deceleration of 6 m/s2 was sufficient to be able to completely avoid collision with the target vehicle and so on. Figure 8 presents the summary of the brake pressure variation study. It is observed that there is an increasing trend between the minimum deceleration required, for the host car, to avoid collision with reference to the relative velocity difference between the host and the target vehicles. This information may be utilized as a starting point for the development of an adaptive AEB system, especially important for the City Traffic Scenarios in which sudden application of a full braking may create a collision risk for the vehicles following the host car.

4.2 Sensor Noise Variation Study

The Sensor Noise Variation tests aim to evaluate the effectiveness of the AEBS under different environmental clutter and noise conditions. The rearward impact scenario is modeled, the car travels at the speed of 50 km/h, the target car moves at a speed of 30 km/h and the sensor noise conditions are varied for each scenario. The AEB system considered in this paper is based on a long range radar, as discussed earlier. The radar has a range of 200m, a horizontal field of view of 10 degrees and an update rate of 100Hz. The AEB system generates a warning at the risk of collision with the slowly moving target vehicle. It is assumed that the driver applies brakes, at which the system applies the maximum possible deceleration. The behavior of the host car, the deviation in the TTC for driver warning is noted down for different sensor noise conditions for the host car. PreScan, using additive Gaussian Noise in the reflection path for the TIS sensor is used to model the environmental clutter typical for Radar sensors.

The sensor noise is varied between 0.5 – 5 deg in azimuth and between 0.5 – 5m in range for the TIS. We observed that the sensor noise in azimuth alone doesn't affect the performance of the system however, for the noise in range greater than 1m, figure 9, there is a large variation in the calculations of the TTC measurements for driver warning. The Sensor Noise Variation study indicates the effects of the environmental noise on the performance of the AEB System. This study may be utilised to improve the logic of the controller and increase its robustness.



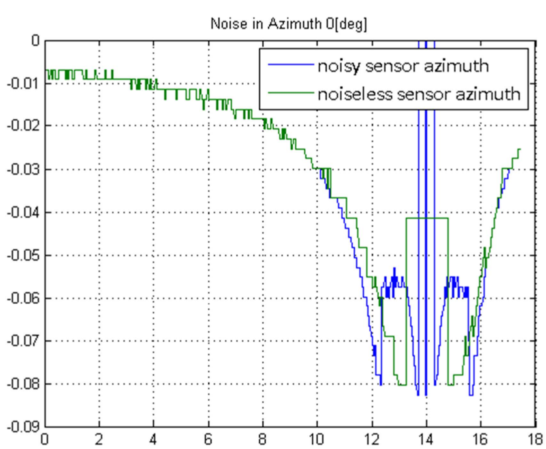


Figure 9. Fluctuations in the Range and Azimuth measurements for the TIS sensor with an additive reflective noise in Range for 1m

4.3 Road Curvature Variation Study

The Road Curvature Variation tests aim to evaluate the effectiveness of the AEBS under different road curvature condition scenarios. The rearward impact scenario is modeled, the car travels at the speeds of 30-100 km/h, the target car moves at a speed of 20 km/h and the road curvature conditions are varied for each scenario. The AEB system generates a warning at the risk of collision with the slowly moving target vehicle. It is assumed that the driver applies brakes, at which the system applies the maximum possible deceleration). The behavior of the host car, if it manages to avoid the collision or not, is noted down for different road curvature conditions for different test speeds for the host car. Three variations for the rearward impact scenario, slowly moving target vehicle are modeled (The worst-case (curvature 150, speed 100km/h) lateral acceleration was noted down to be 5.2 m/s2.).

Experiment	Host Car speed [km/h]	Target Car speed [km/h]	Initial Distance [m]	Radius of Curvature [m]
Curved_500	30-100	20	200	500
Curved_250	30-100	20	200	250
Curved_150	30-100	20	200	150

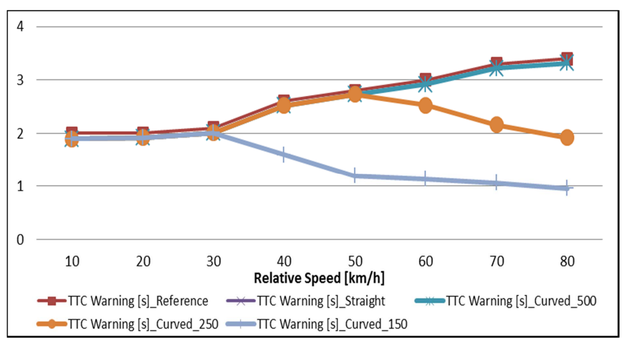


Figure 10. Comparison of TTC for Driver Warning for Road Curvature Variation

Figure 10 presents the comparison of calculated TTC for driver warning for various road curvature scenarios with the reference TTC driver warning values, straight road scenario, for different relative speed conditions. It is observed that the tested system deviates from the desired (reference) performance for a relative speed of about 60km/h when the road curvature is 250m. Similarly, a deviation in the desired system behavior is observed at a relative speed of about 30 km when the road curvature is 150m. The testing shows that the modeled AEB system may not behave as desired for the higher relative speed scenarios on curved roads. This is due to the limited field of view (FOV) for the LRR utilized in the system.

4.4 Results

The PreScan-Matlab simulation of the collision scenario results in the actuation of the host vehicle's AEB system that deploys ***driver warning*** and slows down the car from initial driving velocity to either full stop or lower collision velocity through partial or full braking. The measured variables include the TTC for the driver warning, driver reactions and the collision speed in km/h (if the collision is not avoided) which are then compared with the laboratory experiment test results. The performance of the system can be analyzed using the pop-up alarm cascade, display panel for the AEBS experiments that provide information on the reduced collision speed as a result of system deployment, vehicle velocity profile, vehicle deceleration profile and the TTC timings for each system deployment stage. It may be noted that the user can modify the simulation and system settings: maximum braking pressure, indicator ON/OFF, throttle opening, driver response, driver reaction and brake system delay values.

6. CONCLUSIONS

The presented work shows the use of validated virtual models and laboratory experiments for the design and development phase of AEB systems. The simulation tooling is capable of assessing the effects of the performance of all AEB system components (such as sensors, object detection & interpretation algorithms and vehicle dynamics control algorithms) on the safety performance of the complete ADA system. In the parameter variation study, the effects of various system settings, scenario conditions and also different noise levels of the sensor signals are investigated. The presented parameter variation study shows the benefit of using validated CAE models in the early stages of development in order to (i) avoid identification of design errors in the prototyping phase, and the (ii) selection of relevant critical scenarios for test track testing. VeHIL shows its potential, as a next step to the simulation study, to determine the real system/sensor/controller performance using a series of high quality experimental measurements in the controlled laboratory environment. The advantage of the use of the PreScan-VeHIL tool-chain is that the performance of the system components can be verified in the earlier stages of the development cycle already before the system prototyping phase begins.

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CONTROLLABILITY ASSESSMENT FOR UNINTENDED REACTIONS OF ACTIVE SAFETY SYSTEMS

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ABSTRACT

ISO 26262 requires a controllability assessment for the hazard and risk analysis of automotive E/E systems. Depending on the verifiable controllability, a function may be limited in terms of its intervention options and intensity. For Active Safety Systems this limits their accident-avoidance/-mitigation potential. An analysis of the applicability of ISO 26262 for these systems reveals that it does not address unintended reactions due to incorrect situational analysis of a surrounding perception system, even if the situation for the driver is similar to some of the failure modes. Additionally, the result of the risk assessment depends on the situations chosen. As numerous factors define a driving situation, the possible detailing of these factors is unlimited. Detailing decreases the rate of occurrence of single situations and thereby lowers the required overall safety level. Hence, a method is needed that allows a systematic, verifiable derivation of test situations, including traceability of the detailing. Based on this, for an objective controllability assessment with limited test effort, the minimal sufficient set of relevant scenarios for testing has to be identified.

These scenarios need to have a high probability and impact on controllability. Both factors have to be quantified and evaluated. Based on the analysis of a controllability situation, a strategy is developed to assess the relevance of situations. To quantify the change of uncontrollability in real testing, an objective assessment criterion has to be designed. As a start, the method is applied to emergency braking functions in longitudinal traffic.

The approach begins with the base case and categorizes the factors of a controllability situation. These are weighted with a relevance factor derived from the probability and the controllability. The factor for controllability depends on an assumed or measured increase of uncontrollability caused by the specific situational parameter. By increasing the detailing level, the overall relevance factor for the parameter is derived, to be used on the next less-detailed level.

The assessment criterion for uncontrollability is based on the remaining distance to the point where a crash is unavoidable, the “Point-of-No-Return” (PoNR), and the braking deceleration by the driver. Depending on the driver’s braking force, the PoNR is postponed until the crash will no longer occur. To prove the feasibility of the assessment method, a decelerating leading-vehicle situation is defined. Different deceleration strategies with and without switch-off are used. After initial simulation, the situation is implemented in a real test setup and experiments with naïve drivers are conducted. The results of the objective and subjective evaluation are analyzed and discussed.

The methodology allows the systematic identification of the minimum set of test scenarios for controllability assessment of Active Safety Systems. It quantifies the relevance of influencing factors and in combination with the controllability criterion, can reduce the test effort and increase transferability.

The methodology enhances the controllability assessment according to ISO 26262 [1] to support a systematic choice of controllability test scenarios for Active Safety Systems. A more reliable controllability assessment allows the limits of these systems to be enhanced, increasing the overall traffic safety.

INTRODUCTION

Over the past decade, Advanced Driver Assistance Systems (ADAS) have developed rapidly. Using environment perception systems to assist and support the driver, they are able to avoid a growing proportion of accidents. At the same time, the increasing application of mechatronics-based systems in vehicles means that there is a rapidly growing number of intervention options. The actuators are getting closer to match or even out-perform the capabilities of a human driver. This may lead to the conclusion that traffic safety will soon reach a high level.

To provide safety in public traffic, ADAS depend on information their sensors extract from the surroundings and from the driving situation. Based on this information, they need to predict the situation in the near future and find a suitable and safe counteraction. In most cases, such counteraction is dependent on the present status of the driver. For example, if the driver is distracted, an early warning might be suitable. If the driver is aware of the situation this warning will possibly be too early, a phenomenon often referred to as the “warning dilemma” [2].

To provide reliability, the system needs to be at least as good as the driver in its cognition and perception of the specific situation. Even then, the decision of the driver and the decision of the system may diverge, leading to a reaction which is unintended by the driver.

For public traffic it is necessary to prove that hazards due to failures or unintended reactions are reasonably low. Requirements for the risk assessment of safety-critical electric and electronic systems in case of failures are provided in ISO 26262 [1].

For present-day ADAS, the limiting factor is assumed to be a lack of information or lacking information reliability especially in complex situations. Hence, unintended reactions that may cause potentially critical situations cannot be ruled out completely. To overcome this and still provide safety, a common approach is to limit the operational range of a function. Examples are the limitation to a speed-range or the reduction of the duration and/or the intensity of the intervention [3]. In doing this, the safety performance may be limited as well.

By improving the risk assessment in case of failures or unintended reaction, it is expected that the safety performance can be increased.

REQUIREMENTS OF ISO 26262 AND EXISTING TEST METHODS

ISO 26262 [1] established in 2011 provides requirements for safety processes for electric and electronic systems in the automotive industry. Within the “Hazard and Risk Assessment”, potential failures, the resulting hazards and their causes, have to be identified. To assess the risk, the exposure (E), the controllability (C) and the severity (S) of a hazard have to be estimated and classified in stages (for example C1 – Simply controllable to C4 – Difficult to control or uncontrollable) [1]. Based on these classes, the Automotive Safety Integrity Level (ASIL) is derived according to Table 1.

Table 1.
ASIL Determination Matrix [1]

		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

The ASIL defines the safety requirements of the soft- and hardware components of the function. For example ASIL B requires a maximum allowable random hardware failure of less < 10^{-7} per operating hour [1].

The applicability of ISO 26262 to the case of unintended reactions can be questioned, as it is intended to apply to the functional safety of electric and electronic systems for vehicles up to 3.5 t. Strictly speaking, the approach described there is not necessarily feasible for unintended reactions of ADAS. In these cases, the system works within its specification and a “failure” results from differences between the situation assessment of the driver and of the system. Therefore, unintended reactions are difficult to detect. In contrast to random hardware failures, the expectable rates of misdetection and misinterpretation of a system can be closely connected to the situation and to the utilization profile. As the resulting situation for the driver or other involved persons are considered to be equal, the methodology and testing approach is assumed to be transferable to unintended reactions. However, it is questionable whether the absolute failure rates used for ASIL determination are allowed to be transferred to this problem [3].

According to the processes of ISO 26262, the exposure of the system to a specific situation and the controllability of the incident resulting from the unintended reaction are the two factors that could be influenced in the development of systems. They determine the relevance of potential hazardous situations and thereby allow the identification of the most critical elements for the approval of systems.

Applicable state-of-the-art methods for the assessment of controllability according to ISO 26262 are summarized in the “Code of Practice” [4]. In there, studies with naïve drivers are recommended as they have high validity. However this method is considered to be very time consuming. To achieve an assessment on level C2, at least 20 valid trials are required, without one single uncontrollable event. A detailed statistical analysis shows that the chances of success for this approach are considerably low at 20 trials [5].

Fach [6] describes a controllability study in a dynamic driving simulator, using the crash/no-crash criterion as suggested in the Code of Practice. Neukum [7] uses trials in public traffic to research the controllability of an Adaptive-Cruise-Control function using subjective and objective values for assessment. A combination of a driver model with measurement data of endurance runs is described by Ebel [3]. Again the crash/no-crash criterion is used.

To supplement these techniques and enhance the transferability of results, an additional method for identification of the minimum set of test scenarios and an adjacent assessment method for controllability is developed.

SITUATIONAL DETAILING AND RELEVANCE

For the assessment of controllability, it is necessary to identify situations suitable to reveal the controllability of an unintended system reaction or a system failure. To limit the amount of testing required for the approval, the situations used for testing should be of high relevance for the real use of the vehicle. As a driving situation could be composed of a nearly infinite number of parameters, a methodology for the systematic identification of the minimum set of necessary test cases has to be defined.

Selection of Test Situations

Different approaches for the choice of test situations are used. A common method is the worst case selection, where all relevant parameters are set to the condition where they are assumed to influence the situation in the most negative way. The intention is that the result of this measurement is the worst possible in all situations. If, for example, a controllability approval could be reached in worst case conditions, all other possible situations will have a higher controllability and be less critical. At the same time, the probability of a combination of all situational parameters in the most negative way is assumed to be very low. This approach thereby overestimates the risk in real traffic and may lead to unnecessary limitations of the functionality of a safety system.

Another approach used in validation is to define specific test cases based on the requirements for the function and/or for the adjacent use-cases. In the case of unintended reactions of the function, the exact opposite is needed. Theoretically, these are all possible situations minus the use-cases defining the requirements [8]. In theory a "brute force approach" could also be applied. In this approach all possible situations are identified by combining as many situational factors as possible. The effort for the brute force approach is very high. In addition it is not assumed to be successful in many cases, as it faces two challenges. First, the set of parameters is only theoretically finite, but in practice too high, so there is always a possibility that one parameter has been left out. Second, calculating the probability of the testing situation, by multiplying the probabilities of every situational parameter will result in a situation with very low probability. In line with the methodology of ISO 26262, the exposure factor of all situations could then be so low, that even with a controllability of C3 every function does not need an ASIL of higher than "A" (see Table 1). The more situational parameters used, the more the exposure and thereby the relevance of the single testing situations decreases.

To cope with these challenges a supplementary methodology for the identification of the necessary set of test cases needs to allow the detailing of situational factors on different levels and must take into account the relevance of situational parameters in terms of probability and controllability variation. Additionally it should allow for being based on an "incomplete" set of situations and give assistance in choosing where further detailing may be useful.

To achieve this, the driving situation is analyzed to identify influencing parameters in terms of controllability. These parameters are then classified and detailed within their classes. Based on this, an assessment method is described that considers the change of controllability caused by these parameters and their relevance regarding the use profile.

Parameter of Controllability Situations

The driving situation is composed of many parameters. A common approach is to cluster these in three categories [9]:

- Environment: e.g. weather, lighting, friction coefficient, road, other traffic participants…
- Driver: e.g. driving education, attention, driving capabilities, internal model, fatigue…
- Vehicle: e.g. technical condition, speed, acceleration…

In a generic approach, starting with these three categories, variation factors are identified. Following the approach of ISO 26262 some can be ruled out. For example the technical condition of the vehicle is defined there as "good". Similarly, considering driver behavior, only short term factors have to be taken into account [5]. To avoid interdependencies, the parameters chosen for the situation definition should be as independent of each other as possible.

The influences of these parameters on the controllability of an unintended reaction are then divided in three elements: causes, hazards, and reaction-limiting factors. Based on this, a set of parameter classes has been identified. Table 2 shows the set of parameters used in this paper and examples of their influences on the controllability situation. The parameter *K* represents the index for this class for detailing.

Table 2.
Situational Parameters

Class	Parameter	*K*	Examples of Influences
Environment	Illumination	1	Driver Perception Time
	Precipitation	2	Driver Perception Time, Friction Coefficient
	Traffic Density	3	Hazards, Complexity of traffic situation
	Road Category	4	Lateral Space, Range of Sight
Driver	Visual Distraction	5	Driver Reaction Delay
Vehicle	Lateral/ Longitudinal Acceleration	6	Available Lateral/Longitudinal Force for Avoidance

This set is not necessarily complete and can be discussed, but nevertheless it is considered to be appropriate as a starting point to investigate the feasibility of the controllability assessment method outlined in this paper.

Relevance Weighting on Detailing Levels

As the controllability proportion (p_C) of a function is assumed to be a high proportion (for example C2 ≥ 90 %) of the overall driver collective, for testing it is more feasible to measure its counterpart, the uncontrollability proportion (p_u) according to Equation 1.

$$p_u = 1 - p_C \qquad (1).$$

The reference for the calculation is the controllability level which needed to be approved (for example C2 representing p_{C2} = 90 % and p_u = 10 %).

A situation identification is made for every parameter class in isolation and starts with the identification of the "base case". The base case is a situation which has a high probability, and a high level of controllability. Most changes to situational parameters will thereby lead to a decrease of controllability. Preferably, the base case is simple to reproduce in a testing environment and has an unambiguous impression on the driver.

The detailed parameters have to exclude each other. Every class is split up in more detailed "categories". As the classes are independent of each other, the sum of all probabilities in the categories (on the higher detailing level) adds to hundred percent. In addition and in order to model uncertainties, a "residue" proportion can be added if, for example, no data is available.

The exposure probability of a parameter value ρ and the weighting factor g are characterized by their indices. The first index (*K*) represents the class according to Table 2 with values from 1 to 6. The category index on the first detailing level is q. For each more detailed "sub-category" another index ($r,s,t\ldots$) has to be added, ranging from 1 to the number of detailing subcategories. The dimensions of detailing (sub-)categories could vary.

For every parameter category value q, its exposure probability ($\rho_{K,q}$) is weighted with the weighting factor ($g_{K,q}$) defined as the uncontrollability level (Equation 1) for this specific parameter according to Equation 2.

$$g_{K,q} = p_{u,K,q} \qquad (2).$$

The overall probability vector ($\overrightarrow{W_{K,q}}$) in the respective category q is composed of the probabilities on the next more detailed subcategory (in this example with index $r = 1,2,3,\ldots,n$) according to Equation 3.

$$\overrightarrow{W_{K,q}} = \begin{pmatrix} \rho_{K,q,1} \\ \rho_{K,q,2} \\ \rho_{K,q,3} \\ \cdot \\ \cdot \\ \cdot \\ \rho_{K,q,n} \end{pmatrix} \qquad (3).$$

The overall probability vector is allocated to the weighting vector $\overrightarrow{G_{K,q}}$ composed similarly according to Equation 4.

$$\overrightarrow{G_{K,q}} = \begin{pmatrix} g_{K,q,1} \\ g_{K,q,2} \\ g_{K,q,3} \\ \cdot \\ \cdot \\ \cdot \\ g_{K,q,n} \end{pmatrix} \quad (4).$$

The scalar product of these two vectors is the weighting factor on the next lower detailing level ($g_{K,q}$) (see Equation 5).

$$g_{K,q} = \overrightarrow{W_{K,q}} \cdot \overrightarrow{G_{K,q}} \quad (5).$$

To fulfill the condition that parameter values on same detailing level are excluding each other, Equation 6 must be valid.

$$\sum_{r=1}^{n} \rho_{K,q,r} = 1 \quad (6).$$

Quantification of the Required Detailing Level

The detailing of each situational factor causes effort and requires the collection of additional data. To limit the necessary detailing, a stop criterion is defined. Following the ASIL determination method (see Table 1), the overall controllability for a higher detailing level is only significant if the weighting factor of a parameter in relation to the others on the same detailing level is higher than 10 %. This leads to the stop criteria for further detailing of parameter values according to Equation 7.

$$\rho_{K,q,r}\ g_{K,q,r} \cdot 10 < \max\left(\overrightarrow{W_{K,q}} \cdot \overrightarrow{G_{K,q}}\right) \quad (7).$$

Exemplary Application on Situational Parameters

An environmental factor influencing the driving situation is precipitation. Different forms of precipitation have to be expected in common driving situations. Accordingly, the class "Precipitation" is divided into categories of values excluding each other. These categories are then detailed into subcategories by the strength of precipitation. Table 3 shows the categories, meaning the first detailing level, with exemplary subcategories (second detailing level) and their definitions according to [10].

Table 3.
Example for Categories of Precipitation

Parameter Class	Categories (1st Detailing Level)	Exemplary Subcategories (2nd Detailing Level)	Definition
Precipitation	Without (Base Case)	-	-
	Rain	Violent	> 50 mm/h
		Heavy	10 – 50 mm/h
		Moderate	2 – 10 mm/h
		Slight	< 2 mm/h
	Snow/Ice	Hail	Snow/Ice, Pellets, Hailstones
		Heavy Snow	> 4 cm/h
		Moderate Snow	0.5 – 4 cm/h
		Slight Snow	> 0.5 cm/h
	Fog	Aviation Fog	200 – 1000 m
		Thick Fog	50 – 200 m
		Dense Fog	< 50 m

For clarity reasons, hybrid types such as sleet or freezing rain are not included. If considered to be of relevance, they have to be given their own subcategory. The analysis of similarities concerning the resulting effects on the driving situation may then allow a similar controllability value to be allocated, for example as the value used for light snow.

Following the division to classes and categories, the probability of the factors is needed. If no data is available, the factor has to be included in the "residue". Consequently, availability of data is crucial for the evaluation process. If the data is not available or not considered valid, for a conservative and safe approach the lowest controllability value must be assigned. This concludes that even a small residue causes a low overall controllability.

The data for the probability of parameters used in this example is based on literature [11, 12]. The example includes the first detailing level only, as no reliable statistical data is available for a more detailed analysis. The controllability values and the proportion of the residue are estimated. As no data is available for the base-case it is derived using Equation 8.

$$\rho_{2,1} = 1 - \sum_{q=2}^{5} \rho_{2,q} \quad (8).$$

The result of the relevance weighting according to the described method is shown in Table 4.

Table 4.
Relevance Weighting for the Class Precipitation

g_1	Categories	q	$\rho_{2,q}$	$g_{2,q}$ (estimated)	Product $\rho_{2,q}\, g_{2,q}$
0.070	Base Case	1	0.83	0.05	0.042
	Rain	2	0.09	0.1	0.009
	Snow/Ice	3	0.03	0.5	0.015
	Fog	4	0.04	0.1	0.004
	Residue	5	0.01	1	0.010

The example shows that even this very small residue has a big influence on overall controllability. However, an approval on level C2 ($p_u = 10$ %) is possible in this configuration, if the estimated controllability proportions can be proven for the specific cases.

In summary, the methodology is very dependent on the availability of consistent valid data of occurrence rates for situational parameter and a valid controllability assessment. In addition the methodology is dependent on a good initial controllability estimation to identify the most relevant cases which are worth a detailed analysis or even testing with naïve drivers. In the present paper a simulation model is used for this preliminary estimation.

ASSESSMENT OF CONTROLLABILITY

For the assessment of the situational relevance a controllability criterion is needed. The "Code of Practice" [4] defines the criterion for controllability on a nominal scale. It differs depending on whether or not the reactions of the involved persons are able to avoid the crash. For controllability testing with naïve drivers a more detailed criterion is needed which enables statistical analysis by calculating mean values and variance in the collectives. Therefore, a scaled value with an absolute reference has been developed.

Every driving situation starts on a latent danger level, and the occurrence of an incident leads to an ascent of the actual danger level. Without a counteraction the danger increases until it reaches the level where a crash occurs. A possible counteraction can be carried out by the driver to avoid the crash.

To assess the controllability of a situation at least two requirements must be met. First, the situation must be critical and threatening for the driver to trigger an urgency or emergency reaction [13]. Second, there must be enough reaction time left for the driver to perceive the situation and perform an intervention maneuver, otherwise the controllability will be zero in any case.

From this last requirement it is concluded that there is a limit where the driver needs to start the intervention maneuver to be able to avoid the crash. To describe this limit a distance-based approach is used. In the following this minimum reaction distance is called the Point-of-No-Return. If the driver reacts before reaching the Point-of-No-Return, the next question is whether the reaction was appropriate and intense enough to avoid the collision. Defining the Point-of-No-Return as the last possible distance for starting a lateral or longitudinal intervention means that the intensity of the counteraction needed for intervention increases from the start of the situation to that point where it reaches its maximum and is limited by the maximum longitudinal or lateral force available. This criterion is similar to the Time-to-React (t_{tr}) criterion in a time-based approach. A criterion for controllability situations in longitudinal traffic based on the Point-of-No-Return criterion is described below.

Controllability Criterion

The basic situation is assumed to be a decelerating leading vehicle. In most cases, the driver reacts to that potentially critical situation by braking [14]. The interface for deceleration of the vehicle is the braking pedal and the force the driver applies to it, resulting in a specific travel of the pedal. The brake pressure leads to a deceleration and thereby to a change in the relative accelerations between the two vehicles. The absolute deceleration is mainly limited by the friction coefficient. This limitation leads to a last point where a collision can still be avoided by the driver, the "Point-of-No-Return". Neglecting differences in the brake dwell time (τ_B) between vehicles, the Point-of-No-Return is only dependent on the situational parameters relative velocity (v_{rel}), relative deceleration between the vehicles (D_{rel}) and maximum relative deceleration ($D_{max,\, rel}$). It is determined by the maximum longitudinal deceleration (D_{max}) and the deceleration of the leading vehicle (D_{target}) (see Equation 9)

$$D_{max,rel} = D_{max} - D_{target} \qquad (9).$$

For a constantly decelerating leading vehicle and, for simplification, neglecting the dwell time (τ_B), the Point-of-No-Return can be calculated by Equation 10 [15].

$$d_B(v_{rel}, D_{max,rel}) = \frac{v_{rel}^2}{2\, D_{max,rel}} \qquad (10).$$

Plotting the actual distance between the two vehicles over the squared relative velocity leads to linear relations for a constantly accelerated situation. The resulting graph is not linked with the time but rather directly referenced to the physical contact between the vehicles (d = 0). Thereby, reactions of the driver or a safety system can be depicted and compared to the original situation (without reactions of driver/system) in the same diagram. Figure 1 shows an example for a situation of a constantly decelerating leading vehicle with and without driver reaction.

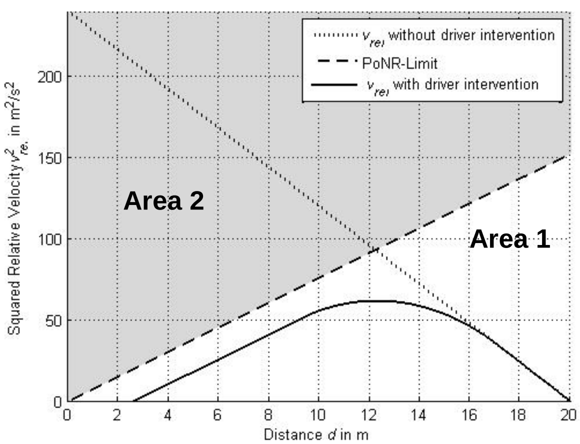

Fig. 1: Controllability graph for D_{target} = 6 m/s^2 with and without driver intervention

The plot enables an easy identification of the controllability. As long as the relative velocity plot is completely located within area 1, the whole situation is controllable. The closer it gets to the Point-of-No-Return-Limit, the more critical the situation would be. Crossing the limit into area 2 the situation will become uncontrollable. Therefore, in addition to the binary crash/no-crash criterion, the plot provides the option of identifying the minimum distance to the Point-of-No-Return within the whole situation ($d_{min,\ PoNR}$).

Assuming the driver does not decrease brake force as long as the situation is critical, it also enables prediction based on the pending decelerations. In Fig. 1 for example, in the event of driver intervention the deceleration reaches a steady state at a distance of 9 m and can be extrapolated.

For each situation it has to be taken into account whether the target comes to a full stop. In this case D_{target} will be zero and the Point-of-No-Return-Limit is defined by D_{max} only. This is also the case for a switch off of the deceleration of the leading vehicle after a defined period. So the results of such a limitation can be analyzed in aftermath. Figure 2 shows the effect of a switch off or stopping target on the Point-of-No-Return.

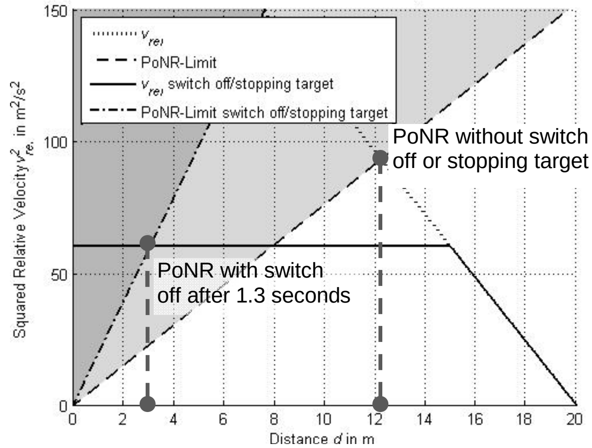

Fig. 2: Controllability graph with D_{target} = 6 m/s^2 without driver intervention

For the analysis and modeling of driver reactions, a time based view is needed in addition. Human processing and action parameters are often measured on a time base. Examples are the overall reaction time, mental processing time or foot movement time [16]. The reaction time limits including the dwell time, can be calculated backwards from the Point-of-No-Return as a function of the relative velocity (v_{rel}) and the distance (d) and included in the controllability graph.

To be able to react in an appropriate way, the driver must perceive and anticipate the situation. To quantify at which point this is possible, the approach relying on the change of the picture size is used. According to [19] the distance at which the likelihood that the driver is able to estimate the criticality of a situation is higher than 50 % ($d_{limit\ 50\ \%}$) is derived based on the width of the target (B_{target}) and the relative velocity according to Equation 11.

$$d_{limit\ 50\ \%} = \left(\frac{B_{target}\ v_{rel}}{0.003\ s^{-1}}\right)^{\frac{1}{2}} \qquad (11).$$

Based on this criterion the, time between the beginning of the situation and $d_{limit\ 50\ \%}$ is derived ($t_{est\ 50\ \%}$).

Choice of Controllability Situations

For identifying situations which are suitable and relevant for controllability testing, in the first step potential hazards are analyzed. For the described scenario, a hazard results from a decelerating leading vehicle in combination with a limited time gap (τ), thereby limiting the reaction time for the driver of the following vehicle. According to the situational parameter classification in Table 2, distances are a characteristic parameter for traffic density ($K = 3$) in longitudinal traffic.

The deceleration of the target vehicle depends on the braking strategy implemented. It determines the development of the situation and the perceivability by the driver. For the present study, braking strategies covering different collision-avoidance variants used on the market are implemented. In addition to constant, full and partial deceleration, a staged strategy is used, as the anticipation for the driver is expected to be more difficult in this case.

In the event of an unintended reaction of the system, it is possible, that the driver of the leading vehicle overrides the braking and thereby switches it off after a specific time period. Additionally it may be an option to switch off the intervention of the collision avoidance or mitigation system after a specific time period, if no driver reaction is detected. This limitation enables to keep the controllability at a high level, if unintended reactions are unavoidable [3]. In [15] a minimum time span of 1.3 seconds is used wherein all drivers are expected to have reacted in case of emergency braking. Based on this, for every strategy a switch off after 1.5 seconds is additionally taken into account. Table 5 sums up the braking strategies used.

Table 5.
Deceleration Strategies of Target Vehicle

Name	**Deceleration D_{target}**	**Duration**
Partial with Switch Off (SO)	6.5 m/s^2	1.5 s
Partial		To Full Stop
Full with Switch Off (SO)	9 m/s^2	1.5 s
Full		To Full Stop
Staged with Switch Off (SO)	Stage 1: 3 m/s^2	0.75 s
	Stage 2: 9 m/s^2	0.75 s
Staged	Stage 1: 3 m/s^2	0.75 s
	Stage 2: 9 m/s^2	To Full Stop

The strategies are combined with suitable time gaps (τ) to compose a driving situation with potentially critical controllability. Following the detailing approach, the classification of time gaps and their probability is based on statistical data of driver behavior according to [20] and [18] and clustered in parameter categories in Table 6.

Table 6.
Classification of Time Gaps

	Parameter Class: Time Gap ($K = 3$)		
	Categories: 1st Detailing Level		
τ	0.7 – 1.0 s	1 – 1.8 s	≥ 1.8 s
q	1	2	3
$\rho_{3,q}$	0.25	0.5	0.25
Comment		Base Case	

Longer time gaps increase the available reaction time for the driver. Thereby, test results of the base case ($q = 2$) can be used for a controllability estimation in category $q = 3$. It can be questioned whether category $q = 1$ has to be considered for controllability assessment, as time gaps below 0.9 seconds are less than half the legal distance and result in a fine, but some drivers do follow at these time gaps [20]. Even though the ISO requires the assessment to cover foreseeable misuse, how to handle cases where the driver intentionally takes a higher risk is an issue that has to be discussed.

Simulation for Initial Controllability Estimation

To obtain the preliminary controllability estimation, a simulation model is used. It represents a decelerating-leading-vehicle-scenario and is capable of simulating the coefficient of friction, speed and deceleration strategy of the leading vehicle. In the past, many studies have gathered data of different elements of the driver reaction in emergency braking with varying situational parameters (see [16], [17] and [18]). These studies provide likelihoods of reaction times, enabling calculation that a driver will react within a specific time (see Table 7).

Table 7.
Reaction Times [17]

	Basic Reaction Time	**Foot Movement Time (Emergency Braking)**	**Transient Brake Time**
5 % Limit	0.13 s	0.13 s	0.1 s
Median (t_{react})	0.40 s	0.18 s	
95 % Limit	0.73 s	0.25 s	

The limits of reaction times according to Table 7 lead to fixed time intervals calculated backwards from $t_{tr} = 0$ (equivalent to the Point-of-No-Return distance-wise). The resulting time intervals ($t_{99\,\%}$, $t_{90\,\%}$ and $t_{50\,\%}$) assuming a combination of the distributions of each reaction time element are shown in Fig. 3.

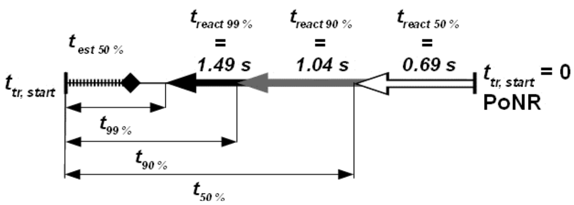

Fig. 3: Time intervals approaching the Point-of-No-Return

The time interval required to obtain a 50 % chance of a correctly estimating the remaining time to collision ($t_{est\ 50\ \%}$) depends on the situation parameters.

The simulation is used to identify the time from the beginning of the situation to the 99 %- ($t_{react\ 99\ \%}$), the 95 %- ($t_{react\ 95\ \%}$) and the 50 %-Limit ($t_{react\ 50\ \%}$) of reaction time and the corresponding controllability levels.

The time gaps chosen for the simulation represent the category ranges according to Table 6. Assuming that uncontrollability increases with decreasing time gap, a value in the lower half of the range τ_{start} = 1.2 seconds is chosen for category q = 2. The simulations are carried out for an initial speed of both vehicles (v_{start}) of 60 km/h. Results are shown in Table 8. Low values for $t_{99\ \%}$, $t_{95\ \%}$ and $t_{50\ \%}$ indicate possibly critical controllability situations.

Table 8.
Simulation Results for τ_{start} = 1.2 s

	$t_{est\ 50\ \%}$ in s	Reaction Time in s (according to Fig. 3)			$t_{tr,start}$	Target Stops
		$t_{99\ \%}$	$t_{90\ \%}$	$t_{50\ \%}$		
Partial SO	0.11	1.03	1.48	1.83	2.52	No
Partial		0.11	0.56	0.91	1.60	
Full SO	0.07	0.05	0.50	0.85	1.54	No
Full		1.19	1.64	0.83	1.52	Yes
Staged SO	0.22	0.50	0.95	1.99	2.68	No
Staged		1.03	1.48	1.30	1.99	Yes

On the basis of the simulation, the conclusion for real testing is that every situation is expected to be controllable for all drivers. To verify these simulation findings, real tests are carried out with naïve drivers.

To estimate the controllability for lower time gaps, the time gap of τ_{start} = 0.9 (q = 1) seconds is simulated too (Table 9). Potentially critical controllability situations are highlighted in grey.

Table 9.
Simulation Results for τ_{start} = 0.9 s

	$t_{est\ 50\ \%}$ in s	Reaction Time in s (according to Fig. 3)			$t_{tr\ start}$	Target Stops
		$t_{99\ \%}$	$t_{90\ \%}$	$t_{50\ \%}$		
Partial SO	0.06	0.30	0.75	1.10	1.79	No
Partial		-0.24	0.21	0.56	1.25	
Full SO	0.04	-0.97	-0.52	-0.17	0.52	No
Full		-0.97	-0.52	-0.17	0.52	No
Staged SO	0.12	0.66	1.11	1.46	2.15	No
Staged		-0.47	-0.02	0.33	1.02	No

As expected, the available reaction times are reduced. For full braking, following the combined distribution, controllability is expected to be approximately 30 %; a switch off does not change the situation anymore. For staged braking without switch off, controllability is expected to be above 90 %. For partial braking without switch off, controllability is expected to be above 95 %. The other reaction times decrease but the reduction in the time gap does not bring about any considerable change in terms of assumable controllability.

While it would be helpful to validate these assumptions by real testing, preceding studies have shown that it is rarely possible to motivate naïve drivers to follow a leading vehicle so closely within the described test setup.

Test Procedure and Layout

For testing with naïve persons a real accident is not possible. However, different techniques can simulate appropriate situations. For example [6] uses a dynamic driving simulator for controllability studies. The validity of simulator findings can be questioned if a critical situation is perceived as threatening due to its virtual impression and in some studies different reaction times have resulted [16]. To overcome this with tests in reality, deformable targets are available. While they provide the option of real contact, they have trade-offs in real appearance.

For the described controllability criterion, it is sufficient to measure the reaction to the point where no Time-to-React is left or a steady state of deceleration is reached. Subsequent reactions can reduce the severity of the crash if the maximum braking force is not reached at the end of the measurements.

A suitable tool providing a highly realistic situation for the following driver is the Experimental

Vehicle for Unexpected Target Approach EVITA [21] (see Figure 4).

Fig. 4: EVITA Tool

The trailer with the real rear-end of a passenger vehicle, called "dummy target", is connected to the towing car by a cable and a cable winch. By opening the brake on the winch and braking the dummy target, a relative velocity to the following vehicle is built up. If a critical relative velocity and distance is met, the winch brake is closed, reaccelerating the dummy target to the speed of the towing car.

It is able to simulate a critical situation in longitudinal traffic with predefined target decelerations without endangering the test persons. It autonomously avoids the accident by applying an acceleration of 2 g to the target to reduce the relative velocity to zero. It has been proven in preceding studies that the test procedure leads to driver reactions similar to real emergency braking situations [20]. The target vehicle of EVITA is used to simulate an unintended deceleration of the leading vehicle due to a false activation. The initial conditions for testing are similar to the simulation conditions. As the drivers are in charge of keeping a constant distance, the time gap at the beginning of the situation varies within 1.2 and 1.5 s.

The following test vehicle, named ego vehicle, is equipped with a radar sensor that measures the relative velocity and the relative distance between the two vehicles. As a reference, the absolute speed of the ego vehicle is measured. The ego vehicle is equipped with a mechanical brake assistant that supports the driver in an emergency stop. In addition the driver´s behavior and foot movement are recorded by high speed cameras showing the driver´s face, the pedals and the headway.

The tests are carried out on a closed test track with test persons who are not informed about the intentions of the testing. In addition to the objective values of controllability, every test person has to answer a questionnaire evaluating the subjective controllability.

The EVITA Tool is capable of simulating a minimal Time-to-Collision of approximately 0.9 s, before it is accelerated. Depending on the scenario and the driver reaction, the Point-of-No-Return cannot be reached in every case. In the event of early and intense driver reaction, this is in fact very likely. To identify $d_{min,PoNR}$ in these cases, the deceleration of the ego vehicle at the end of the test, marked by the acceleration of the EVITA target vehicle, is extrapolated at a constant level. This approach is considered to be conservative, as it refuses the option of the driver to increase the brake pressure later in the situation. In case the driver reacts early, this method may lead to situations where the collision cannot be avoided by the deceleration of the ego vehicle at the end of the test even though there is enough time left to intensify the brake pressure and avoid the collision. To determine this in case of uncontrollable trials, the time to apply full deceleration is calculated additionally.

Test Results

The measured data are analyzed to identify the driver reaction times, defined as the time to contact the brake pedal, the minimum distance to the Point-of-No-Return in testing ($d_{PoNR,\ test}$) and the extrapolated end distance ($d_{min,\ end}$) assuming constant accelerations. Figure 5 shows an example of testing data with extrapolation.

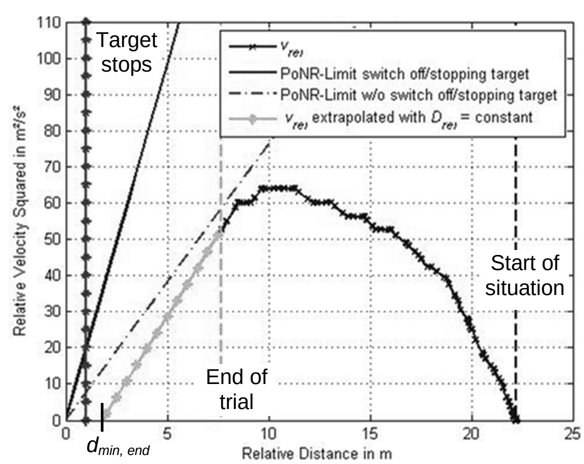

Fig. 5: Example measurement data with extrapolation

Driver reaction times are measured from the beginning of the situation to the contact with the brake pedal, including the mental processing time and the movement time. Figure 6 shows the results of the reaction time in a cumulative distribution function, including the $t_{est\ 50\ \%}$ values based on the simulation, which are illustrated as vertical lines in corresponding colors.

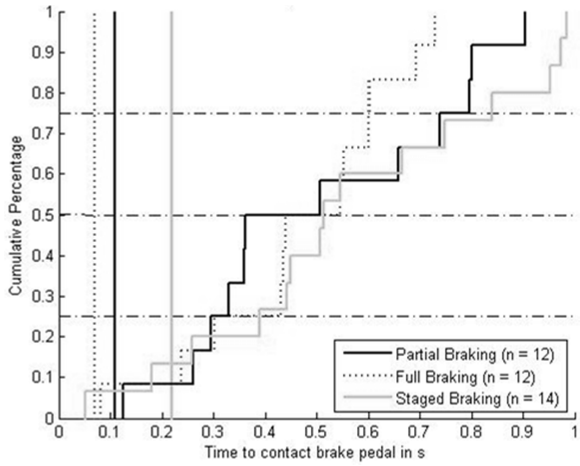

Fig. 6: Reaction Times depending on braking strategy

These results mainly match the preceding assumptions about the reaction times according to [18], but lack the proportion of reaction times above one second.

The cumulative distribution of the maximum deceleration reached at the end of the test is shown in Figure 7.

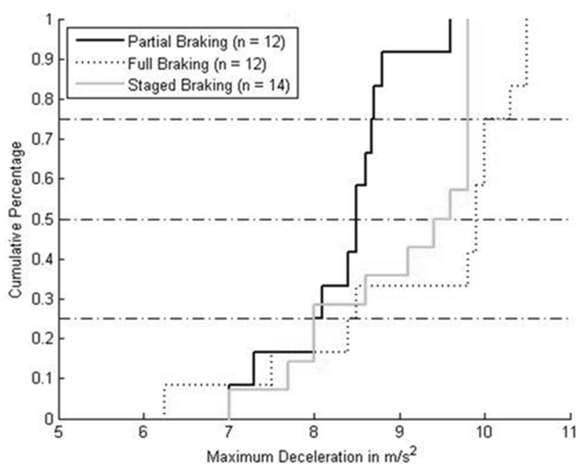

Fig. 7: Maximum decelerations depending on braking strategy

The distribution shows that the intensity of braking depends on the deceleration of the target. For full braking, the distribution can be falsified to follow a normal distribution. For partial and staged braking no statement can be derived. Partial braking and full braking can be proven to be significantly different. This indicates that the driver's reaction depends on the evolvement of the situation.

In the next step, the controllability proportion is analyzed based on the extrapolation with constant acceleration with and without switch off of the braking. Figure 8 shows the minimum distances to the target at $v_{rel} = 0$ ($d_{min,end}$) with switch off.

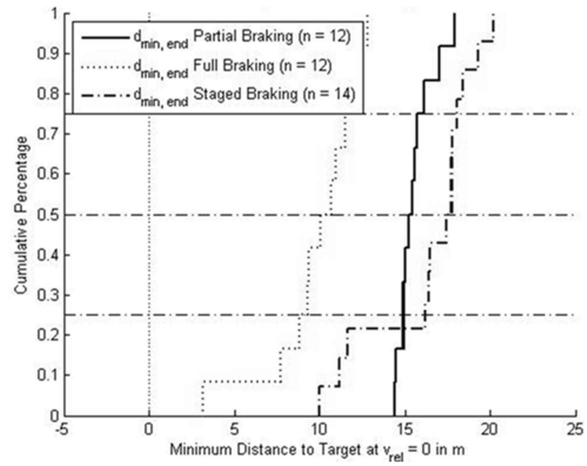

Fig. 8: Minimum distance to target extrapolated for braking strategies with switch off

The differences between partial and staged show nearly significant differences (α = 5.38 %) the others are significant different to each other. However all tests are controllable if the braking of the target is switched off after 1.5 s.

In comparison, Figure 9 shows the results without switch off.

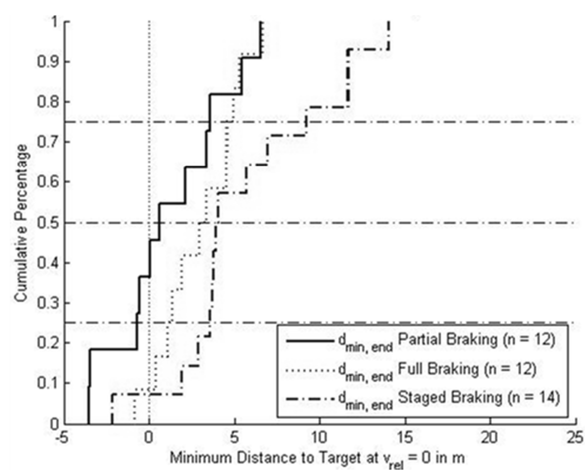

Fig. 9: Minimum distance to target extrapolated for braking strategies without switch off

The differences between partial braking and staged braking are significant.

According to this analysis, partial braking has the highest proportion of potential uncontrollability. In parallel, partial braking shows the lowest mean value for the maximum deceleration. However, the conclusion that partial braking is most critical is not necessarily valid. As described earlier, all drivers react within the first second after the beginning of the situation. If a positive relative deceleration is reached within this reaction, v_{rel} decreases approaching the target. Due to limitations of the test layout, in many cases the trial will be canceled without reaching the Point-of-No-Return. In these trials, the driver still has time left at the end of the trial to increase brake pressure to maximum and avoid collision. This remaining time is called Time-To-Full-Deceleration (t_{tfd}). For the trials considered to be potentially uncontrollable, the minimum distance to the Point-of-No-Return ($d_{PoNR, test}$) and the acceleration at the end of each trial ($D_{end, test}$) in comparison to the Time-to-Full-Deceleration and the minimum extrapolated distance ($d_{min, end}$) ranked by $d_{PoNR, test}$ are included in Table 10.

Table 10.
Analysis of Potentially Uncontrollable Trials

	$d_{PoNR, test}$ in m	$D_{end, test}$ in m/s^2	t_{tfd} in s	$d_{min,end}$ in m
Partial	1.09	8.4	0.13	- 2.49
	4.16	8.1	0.77	- 1.00
	5.27	7.0	0.84	- 3.43
	7.58	8.6	0.98	- 0.52
	9.21	7.3	1.65	- 0.70
Full	6.44	8.4	0.76	- 0.86
Staged	1.34	7.0	0.14	- 2.12

In most cases, the time to increase brake pressure is well above the reaction times previously analyzed. It is assumed that the drivers can react to the evolvement easily and still control the situation. In two cases the t_{tfd} is very short. A concrete controllability assessment is not possible in these cases. Strictly following a conservative approach these cases must be considered to be uncontrollable as no evidence for controllability can be found. Following this argumentation the resulting uncontrollability proportions of the trials ($p_{U, Test}$) and the relating number of uncontrollable trials ($n_{U, Test}$) are summarized in Table 11.

Table 11.
Uncontrollability Proportions

	n	With Switch Off		Without Switch Off	
		$p_{U, Test}$	$n_{U, Test}$	$p_{U, Test}$	$n_{U, Test}$
Partial	12	0.00	0	0.08	1
Full	12	0.00	0	0.00	0
Staged	14	0.00	0	0.07	1

The relevance factor is calculated according to these results, assuming equal controllability for parameter time gap $q = 2$ and $q = 3$ and doubled uncontrollability from $q = 2$ to $q = 1$ with a minimum uncontrollability of 5 %. The results based on simulation (see "Simulation for Initial Controllability Estimation") and tests are included in Table 12.

Table 12.
Relevance Estimation

		Parameter Class: Time Gap ($K = 3$)		
		Categories: 1st Detailing Level		
q		1	2	3
$\rho_{3,q}$		0.25	0.5	0.25
Partial SO/ Staged SO	$g_{3,q}$	0.05	0.00	0.00
	g_3	0.0125		
Partial	$g_{3,q}$	0.05	0.08	0.08
	g_3	0.10		
Full/ Full SO	$g_{3,q}$	0.70	0.00	0.00
	g_3	0.175		
Staged	$g_{3,q}$	0.10	0.07	0.07
	g_3	0.0775		

Results of Subjective Evaluation

The questionnaire showed that all participants were urged to brake (see Fig. 10).

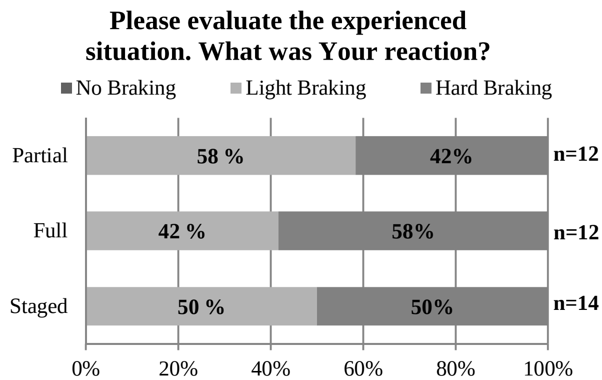

Fig. 10: Subjective evaluation of braking reaction

Even though the overall trend is as expected, it has to be highlighted, that this does not match the results of the distribution of maximum decelerations according to Figure 4. The maximum decelerations could possibly be influenced by the braking assistant, but even then, the function must be triggered by the driver reaction (pedal actuation speed, time to change pedals). The braking assistant should only support the driver if these parameters indicate an intention for an emergency stop. In conclusion the driver seems to be not very reliable at judging his/her own reaction in the aftermath.

In the next step, the risk judgment of the situation is analyzed (see Figure 11).

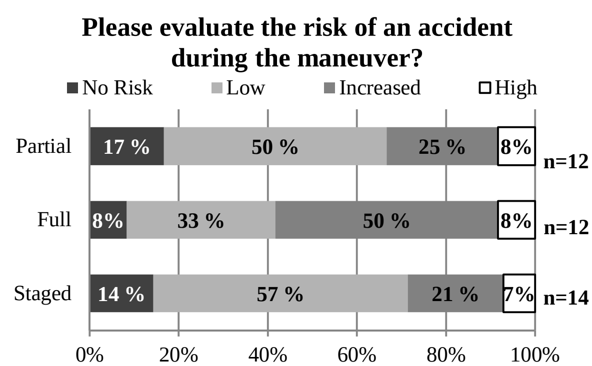

Fig. 11: Subjective evaluation of accident risk

The subjective risk evaluation is relatively similar between partial braking and staged braking. For full braking, the risk is judged to be higher. In Figure 12, the results are compared with the subjective controllability evaluation.

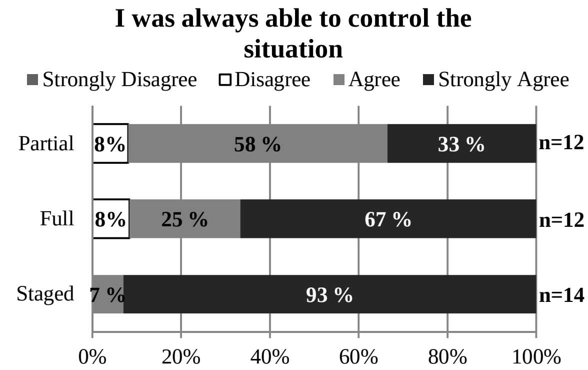

Fig. 12: Subjective Controllability evaluation

It stands out that the proportions of high risk are the same as the “disagree” of controllability for the partial and full collective. A detailed analysis shows that the statements do not directly correspond to each other. Even more remarkably, all trials which are potentially uncontrollable are subjectively evaluated with “Agree” or “Fully Agree”.

Figure 13 shows the direct corresponding proportions between the driver judgment of subjective reaction intensity and subjective controllability.

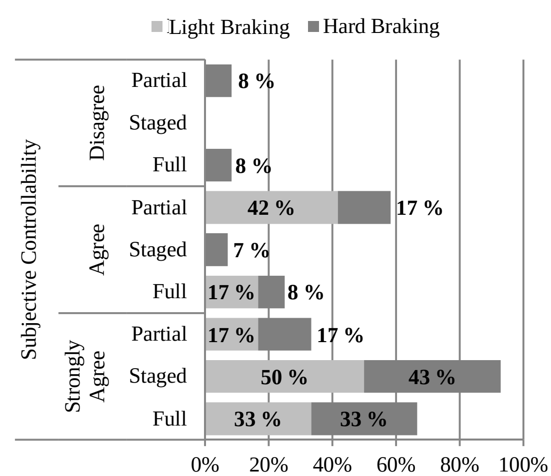

Fig. 13: Subjective Controllability versus reaction overall

For braking strategies with switch off the assessment is correct, with some drivers being more cautious. For braking strategies without switch off, the driver judgment is not correct for some situations, however as they may not approach the Point-of-No-Return during the maneuver, they have less chance to perceive the criticality of the situation.

CONCLUSIONS

A method for identifying and selecting testing situations for controllability has been described and exemplarily applied for a situational parameter. As a next step an assessment method for the controllability assessment was outlined and tests with naïve test subjects were carried out for the identified base case. The testing shows the feasibility of the criterion for subsequent analysis of different situation evolvements, for example considering a switch off of the leading vehicle deceleration.

For strategies with switch off after 1.5 seconds, all trials can be assessed as controllable. Without switch off, the assessment with a simple extrapolating method shows an uncontrollability proportion of one of fourteen trials (7.1 %) for staged braking, one of twelve trials (8.3 %) for full braking, and five of twelve trials (41.7 %) for partial braking. A more detailed analysis reveals that in most of these uncontrollability cases more than 0.75 seconds are available to increase brake pressure and avoid the collision. Considering the remaining time only one trial (8.3 %) for partial braking and one trial for staged braking (7.1 %) are considered to be uncontrollable as the opposite cannot be argued to be valid.

The simulation of lower time gaps indicates that more critical situations are worth testing in real life. However no applicable way to motivate naïve drivers to follow that close was found in the past.

In general, the number of trials per braking strategy used in the present study is relatively low. To further validate the results, the collectives should be enlarged to improve the validity of the assessment. In addition, testing with distracted drivers should be carried out to broaden the knowledge on inattentive drivers.

The test method with EVITA used in here proved suitable for the intended goal. For critical situations where the driver reacts late, it is able to come close to the Point-of-No-Return and trigger a suitable driver reaction. In cases where the driver reacts early but not intensely enough, the method is limited, however these situations are not expected to be most critical.

ACKNOWLEDGEMENTS

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SAFETY ASSESSMENT OF AUTONOMOUS EMERGENCY BRAKING SYSTEMS ON UNBELTED OCCUPANTS USING A FULLY ACTIVE HUMAN MODEL

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ABSTRACT

This paper assesses the safety benefits of a typical Autonomous Emergency Braking System (AEBS) followed by a subsequent 25mph rigid wall impact using a 50th percentile active human model including full muscle activity behaviour. Occupant kinematics as a function of various postures and states of awareness are investigated to determine the degree of out-of-position and their respective chest, neck and head injuries.
The study concludes that the Madymo Active Human Model is suited to model active safety scenarios and that the generated kinematics and injuries provided are plausible.
The study has established that, within the active safety scenario investigated, the occupant's kinematics depend on the seat friction coefficient, arms' kinematics and the level of awareness. Overall, it has been observed that for a reflex delayed response of less than 120ms that chest, neck and head injuries values for gripping the steering wheel with 2 hands were comparable for a given value of seat friction. Alternatively, occupants with 1 hand on the steering wheel (holding a mobile phone for example) were out of the airbag deployment zone after 1.1s of extreme braking regardless of their state of awareness and seat friction value.

INTRODUCTION

Passive safety has for many years reduced the number of fatalities on the roads. However, its effect on occupants' safety has now stabilised, meaning that new safety features, like active safety are needed to further reduce the number of casualties [1]. These active safety features vary from Autonomous Emergency Braking Systems (AEBS) aiming at reducing vehicles speed prior to collision occurring in order to reduce the vehicles kinetic energy on impact to a minimum [2] to automatic lane change.
An initial method of assessing the effect of active safety involving an improved airbag model [3] and 1g pre-brake scenario on an occupant was undertaken [4] using a passive human model. Further implementations and details were incorporated and published [5], including a controlled spine allowing the occupant to sit straight and balance its own weight. This study however has shown that muscle activation was necessary as the occupant's kinematics during the pre-braking phase was independent of its stance. In order to remedy this, volunteer physical tests were performed under low 'g' sled tests [5] to derive human occupant target muscle activity curves as well as an active human computer model [7]. This new active human computer model still required some improvements as some of the muscle activity [9] timing and controller stiffness' needed further developments. It did however show some important findings; in some cases the duration of the AEBS pre-braking phase moved the occupant away from the airbag effective envelope in case of a subsequent impact.
This paper will initially focus on the validation of the new Madymo 7.4.1 Active Human Model in an unbelted scenario which will be used throughout this paper. Occupant kinematics due to various postures, state of awareness will be investigated to

determine the degree of out-of-position and their respective chest, neck and head injuries.

VALIDATION OF AN UNBELTED ACTIVE HUMAN MODEL IN LOW 'G' SCENARIO

The first stage of the study required the calibration of the latest active human model in a lap-belt scenario under low deceleration [10][11]. It is believed that this scenario is the closest to an unbelted scenario without potentially injuring the volunteers.
Utilising the published sled model, it was possible to calibrate the muscle activity controller values in order to correlate the lap-belt sled tests under 1g frontal motion. The controller scalar value is set such that the limbs' position are maintained under the influences of external disturbances.
The seat friction value used between the seat and the human model was assumed to be 0.5 [8].
It was discovered that the spine, hips and arms controller were already suitable for replicating this test (*Figure **1***).

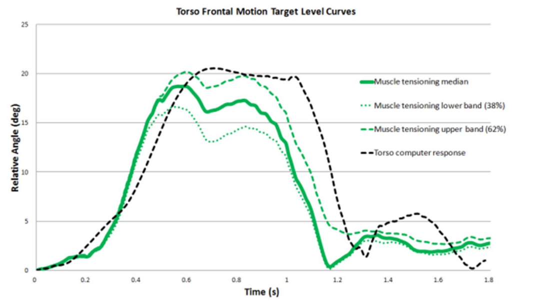

Figure 1. Correlation of torso motion in 1g and lap-belt scenario.

In a lap-belt scenario, the torso rotates more than in a 3 point belt configuration. Consequently, the neck muscle activity controller had to reproduce the fact that the neck flexion was increased (Figure 2) from the original model calibrated for a 3 point-belt [10].

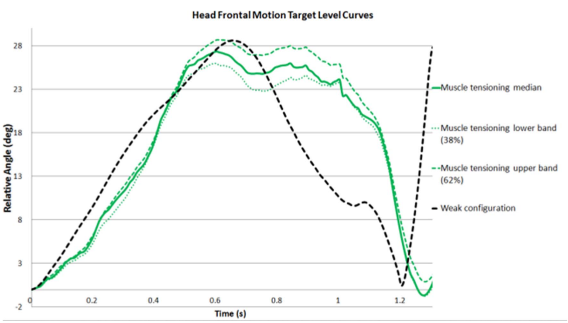

Figure 2. Correlation of head motion in 1g and lap-belt scenario.

The neck controller value was therefore modified to 0.6, whilst keeping all the original controller values to '1', as indicated in Table 1.

The proposed lap belt model's kinematics have a similar response shape and amplitude to the test results, especially for the torso (*Figure **1***). The head's relative angular rotation magnitude was comparable with the physical tests (Figure 2). Nevertheless the head relative angular motion returns to its original position faster than in the test. The model controllers being encrypted, it was not possible to make any further investigations into the head controller scalar value.

Table 1.
Updated Madymo 7.4.1 controller values for unbelted occupant modelling.

Spine	Neck	Arms	Hip	Co-contraction	Reaction time (s)
1	0.6	1	1	0	0

It has to be noted that this current model is not capable of leg bracing. The "Co-contraction" field in Table 1 refers to neck bracing, which was set to "0" as the volunteers had no cognitive input of the test, i.e. were unaware of the start of the sled motion.
The active human model configuration listed in Table 1 was used throughout the entirety of this paper.

DRIVERS' KINEMATIC STUDY

Study setup

The aim of this section is to evaluate the kinematics of an occupant under unexpected 1g emergency braking in different states of awareness, in a generic vehicle environment. As such, no bracing is applied prior to the braking event taking place.

The parameters which will be considered in this study are the seat friction parameter and the state of awareness of the occupant. Seat friction accounts for the evaluation of tendencies in lower extremities load paths, i.e. footrest and pelvis.
The seat friction coefficient in vehicles is of the order of 0.8 [7]. Nevertheless, values utilised for the correlation 0.5 and lower (0.3) were studied to evaluate the spread of the response to this variable. The seat model was constructed from planes with a stiffness characteristics extracted from an accident reconstruction technical report [12]. In all instances, it was assumed that the friction between the feet and the floor to be 0.85 representing rubber sole shoes to a carpet.

The awareness level can vary greatly. A "very aware" person has a reflex response time of 30ms; an "aware" occupant of 120ms, which can be modelled as a 'motor reflex delay' in the human model [11].

The hand is attached to the steering wheel using a RESTRAINT.POINT command in Madymo with a maximum grip force level of 400N [15][16], to simulate the hand release.

The list of normal awareness computer runs are listed in Table 2.

Table 2.
Normal awareness computer setups

Run number	Stance	Reflex time (s)	Human to seat friction
Run 11	FMVSS208	0.030	0.5
Run 11a	FMVSS208	0.030	0.3
Run 11b	FMVSS208	0.030	0.8
Run 21	FMVSS208	0.120	0.5
Run 21a	FMVSS208	0.120	0.3
Run 21b	FMVSS208	0.120	0.8

Prior to performing the kinematics study, the occupant was positioned in the vehicle using a 1g vertical 'Z' for the duration on 1.5s to balance the occupant with its environment. During the 1g emergency braking, the 1g vertical gravity field was maintained.

The forward braking pulse was applied on the human model with the cabin and airbag system set as static. The pulse shape had a well documented characteristic as illustrated by Figure 3 [5].

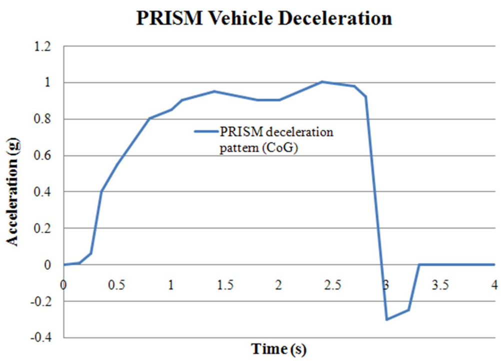

Figure 3. PRISM project. Straight line braking. Vehicle deceleration.

Results of the occupant kinematics' study of standard grip stance ("very aware" or "aware")

The first results concerning the seat with very low friction indicated that the driver's pelvis was sliding forward until the leg contacted the dashboard, as shown in *Figure 4*. The pelvis is sliding because of the lowest resistance provided by the seat relative to the direct loading of the arms.

The torso (solar plexus) almost stayed still (+0.05m forward motion from original position, +X in *Figure 4*) due to the resistance of the arms, which consequently moved the head away from the airbag (-0.05m rearward motion from initial position, -X in *Figure 4*).

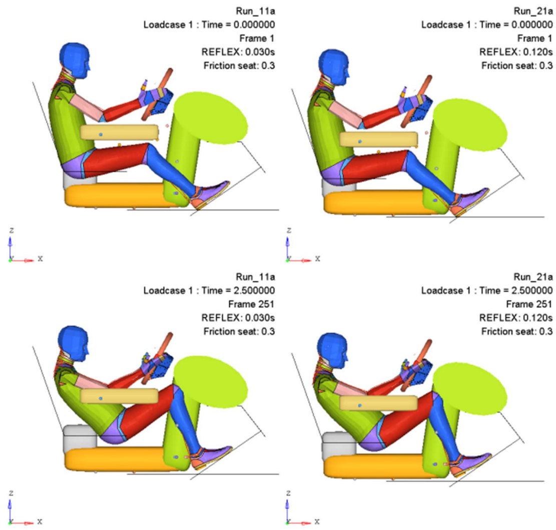

Figure 4. Scenario with seat with friction set at 0.3 (30ms and 120ms awareness displayed Left to Right) at time 0s (top) and 2.5s (bottom).

It was noted that for a very low seat friction, the occupant kinematics was very similar for a "very aware" and "aware" person, especially after 0.5s for the top of the head as well as the solar plexus, as can be noted in Figure 5 and Figure 6, where the displacement curves mostly overlap during the duration of the event.

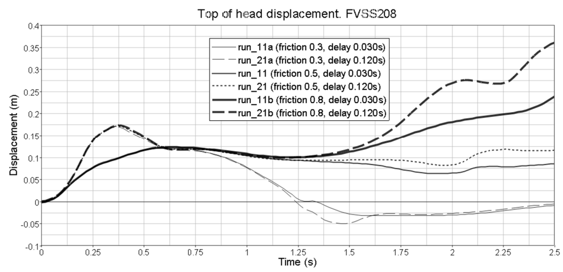

Figure 5. Summary of displacement of top of occupant's head.

It can be noted in Figure 5 that the head has a flexion motion due to the 1g braking pulse which is greater for a motor reflex delay of 120ms than 30ms, as the neck muscles are activated later. When a slower reflex occurs, it takes 500ms to match the head motions of an occupant with a faster reflex.

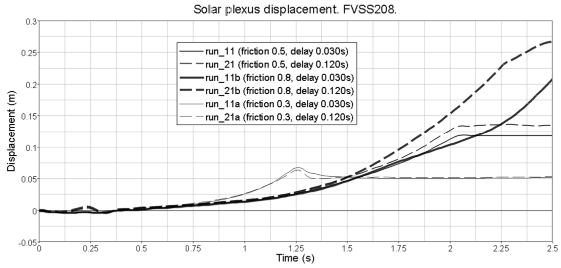

Figure 6. Summary of displacement of occupant's solar plexus.

It can be noted in Figure 6 that, for the same seat friction value, the solar plexus has a greater linear motion the longer the motor reflex delay.

Increasing the seat friction parameter increases the sliding force responsible for the occupants' motion. As illustrated in Figure 7, increasing the friction from 0.5 to 0.8 increases the resistive force to motion from 500N to 650N.

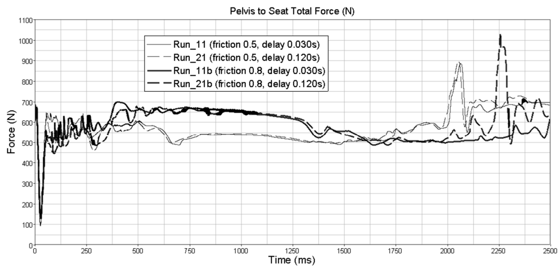

Figure 7. Occupant force on pelvis a function of seat friction and awareness.

Figure 7 also suggests that a motor reflex delay less than 120ms does not have an influence on the seat force due to friction. The human model used has a stabilising spine which will naturally keep the occupant seating straight and hence transfer the load onto the seat. The mass transfer looks very noisy early in the seat force readings (*Figure 7*), which may be caused by the repositioning of the human model from the initial gravity positioning as well as the early muscle activity which affects the heads' forward motion (flexion). Looking at scenarios with greater seat frictions, i.e. 0.5 and 0.8, it can be observed that the kinematics are different initially due to the fact that the seat friction resists the pelvis motion and forces the torso to rotate towards the steering column. This is clearly illustrated in *Figure **8*** and *Figure **9***.

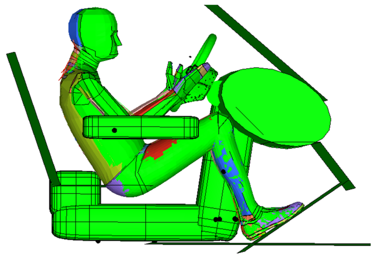

Figure 8. Comparison of occupant kinematics for seat friction 0.5 (30ms and 120ms awareness displayed in blue and green respectively). Pre-braking duration of 2.3s.

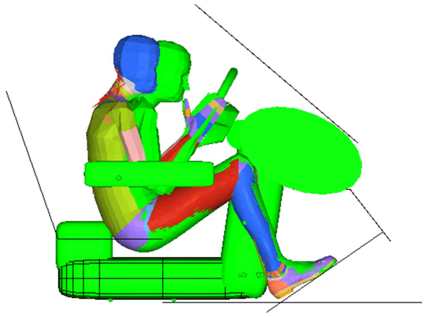

Figure 9. Comparison of occupant kinematics for seat friction 0.8 (30ms and 120ms awareness displayed in blue and green respectively). Pre-braking duration of 2.3s.

This suggests that the higher the seat friction the greater the torso rotation as the relative speed between the pelvis and the torso increases.

Looking at the reflex levels, Figure 8 and Figure 9 suggest that a slower reflex leads to a closer thorax position relative to the steering column.
Indeed, with a slower reflex, the velocity of the torso (measured at the solar plexus) is higher from approximately 1.2s, as the muscle activity in the human model is lagging. With increased velocity, the momentum is increased.

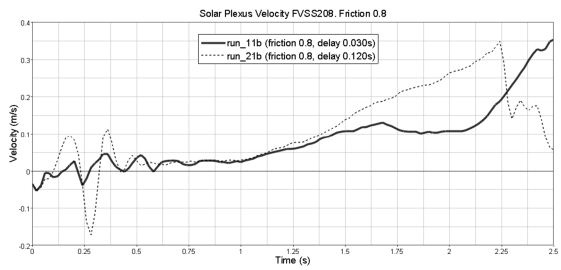

Figure 10. Velocity of human model's solar plexus.

As the hands are restrained on the steering wheel by a RESTRAINT.POINT command with no torque reaction, the arms rotate at the steering wheel attachment to compensate for the momentum.

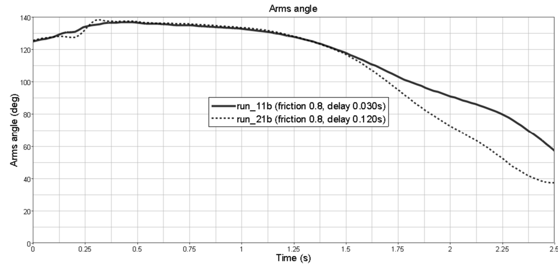

Figure 11. Occupant's arm angle change (deg).

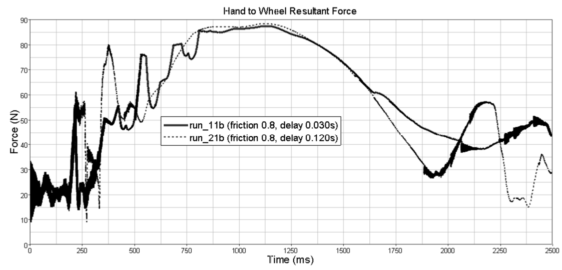

Figure 12. Hand force on the steering wheel.

As illustrated in Figure 11, the occupant's arm's angle starts to reduce from run_11b ("very aware") to run_21b ("aware") at time 1.5s. The force exerted on the steering wheel is reduced (Figure 12) and the occupant is therefore closer to the steering wheel, as illustrated in *Figure **9***.

Results of the occupant kinematics' study of Mobile Phone stance

Using the same model setup as the 2 hand grip, removing the left hand from the steering wheel and raising to the ear level, it has been shown that the coefficient of friction had a great importance in the position of the occupant using a mobile phone.

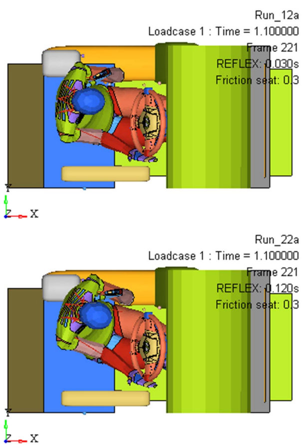

Figure 13. Kinematics results of mobile phone stance friction 0.3. "Very aware" (top), "aware" bottom.

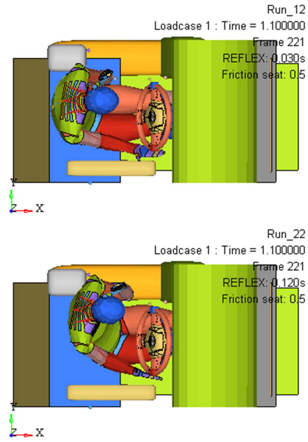

Figure 14. Kinematics results of mobile phone stance friction 0.5. "Very aware" (top), "aware" bottom.

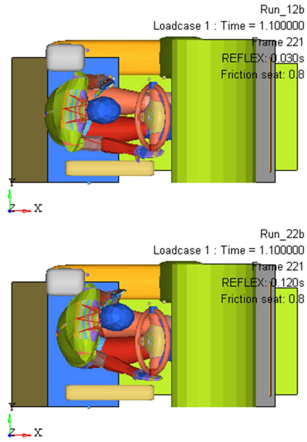

Figure 15. Kinematics results of mobile phone stance friction 0.8. "Very aware" (top), "aware" bottom.

*Figure **14*** and Figure 15 suggest that:

- The greater the friction, the more 'central' the occupant is situated (Y direction in *Figure **15***)
- The faster the motor delay, the more 'central' the occupant is situated (Y direction in *Figure **15***)

Using this latest Madymo human body model, it was possible to re-confirm that a breaking duration in excess of 1.1s positions the occupant out-of the airbag zone of influence, as previously reported [9]

Conclusions on the driver kinematics study

The driver kinematics suggest that the occupant needed to have a good level of awareness (motor reflex delay < 120ms) to resist an unexpected AEBS with no Frontal Collision Warning (FCW).

An occupant using a mobile phone will be in the airbag envelope up to 1.1s of AEBS braking duration with no FCW. Should the duration last longer and should an impact occur, then the occupant will not have any restraint systems to protect it.

In all standard grip starting positions, i.e. with the 2 hands on the steering wheel, the study shows that the human model will resist the deceleration up to a breaking duration of 2.5s (computed for all runs) even though it will move closer to the steering wheel. No hand loads has exceeded the 400N threshold level.
All the run comparisons are listed in *Figure* ***16*** and *Figure* ***17***.

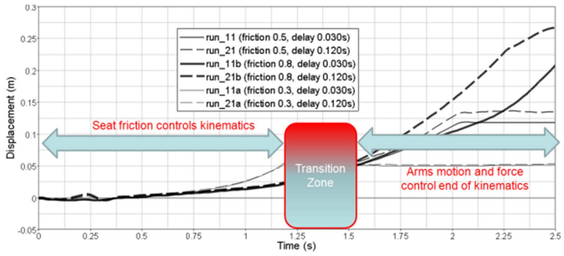

Figure 16. Summary of Solar Plexus displacement (all runs).

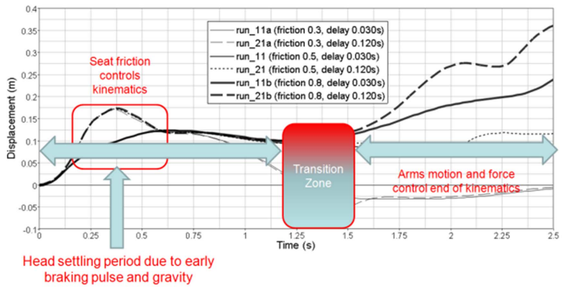

Figure 17. Summary of Top Head displacement (all runs).

Following the study it can be concluded that the first component of the occupant motion is the seat friction, which controls the first 1.0s of the motion. The second part of the motion is due to the motion of the arms which is a result of the own increased kinetic energy as well as possibly the torso's kinetic energy.

Higher friction leads to higher relative velocities from the pelvis to the thorax, hence greater energy of rotation of the thorax relative to the pelvis, leading to increased rotation of the arms, reduction of grip force and consequently closer proximity to the steering wheel.
Considering Figure 16 and Figure 17, the change of energy transfer comparing 2 occupants having different motor reflex delay, i.e. awareness, is difficult to pinpoint accurately.

From the results obtained, a 'transition zone' has been evaluated from the graphs which bands the possible starts of the increase in kinetic energy from the torso. This zone starts around 1.0s and finishes at 1.5s.

As a summary, considering all the variables in this posture study (seat friction, reflex delay and braking duration), it can be concluded that the active human model's kinematics are, in a 1 hand and 2 hand steering wheel grip, reasonable.

DRIVERS' INJURY STUDY

Background and study setup

The aim of this section is to investigate the effects of occupant injuries when vehicles are fitted with AEBS and assuming that full brake is applied on an unbelted occupant with no FCW. The occupant will have a reflex behaviour and not a bracing one as the braking event is sudden and unforeseen.
This study will compare the occupant protection level based on a standard FMVSS208 rigid wall crash test (25mph) against a 1g vehicle deceleration until the vehicle reach 25mph, then followed by a rigid wall impact.

This deceleration will cause the occupant to be out-of-position (OoP) before the impact takes place, as illustrated in *Figure* ***18***.

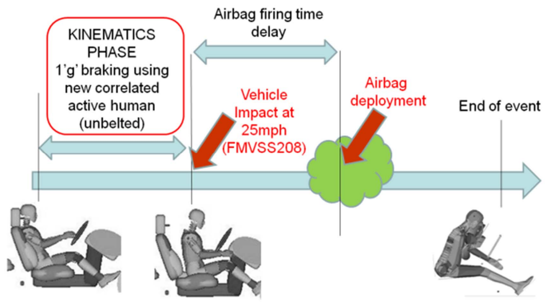

Figure 18. Severe braking scenario followed by rigid wall impact (airbag fire time set to 10ms).

Following the kinematics study, injuries have been extracted for chosen scenarios. The scenarios with the friction parameter of 0.3 have not been further analysed as the occupant's head has moved away from the airbag (*Figure* ***13***).

Cases where head and thorax positions lie within the airbag envelope were favoured.

The crash phase will utilise the pre-braking occupant position which will be re-mapped into an environment with 1g vertical gravity loading and the vehicle crash pulse.

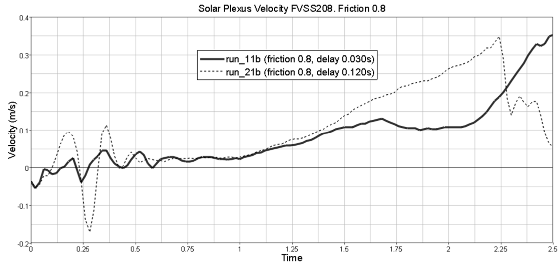

Figure 19. Solar Plexus Velocity for a seat with a friction of 0.8.

Due to the fact that the solar plexus velocity is low velocity (0.35m/s), as illustrated in Figure 19, it was assumed that the occupant was in a state of equilibrium relative to the steering wheel before the accident event starts.
This split-run strategy was used to improve the CPU runtime and allow this study to be performed.

The scenarios with the friction parameters of 0.5 and 0.8 were selected, considering 3 braking durations aiming to reduce the vehicle from its original cruising speed down to 40km/h (25mph) [7], as listed in Table 3.

Table 3.
Braking duration to reduce vehicle speed back to 25mph

Vehicle start velocity (km/h)	60	80	100
Time to reach 25mph (s) under extreme braking	1.1	1.7	2.3

The vehicle crash pulse information utilised has been obtained from previous research [9]. To allow a qualitative comparison between the injuries, it has been necessary to scale the magnitude of the input crash pulse by 65% in order to generate a safe vehicle under FMVSS208 unbelted criteria.

The scaling of the crash pulse was done as the origin of the vehicle from which the airbag computer model was not known, as well as its engine variant, interior type (friction), ergonomics, crash pulse and steering column characteristics [18][19].

In the study undertaken, each occupant starts from a slightly different position due to seat friction values and braking durations before the crash pulse is applied. As a consequence, it is not possible to categorically state the exact cause of each injury value recorded in *Figure **20*** to *Figure **25***.

Results for the standard grip stance

All Neck Injury values (Nij) are well below the legal limit of 1, hence have not been plotted.

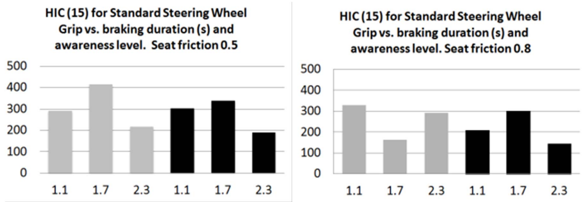

Figure 20. HIC (15) for Standard Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

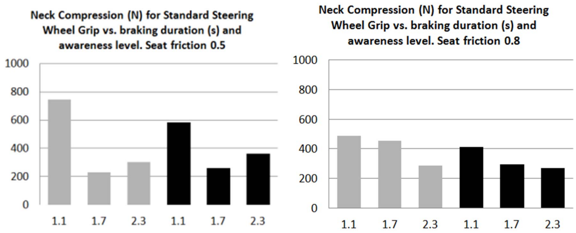

Figure 21. Neck Compression for Standard Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

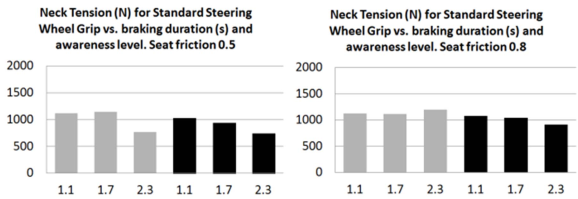

Figure 22. Neck Tension for Standard Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

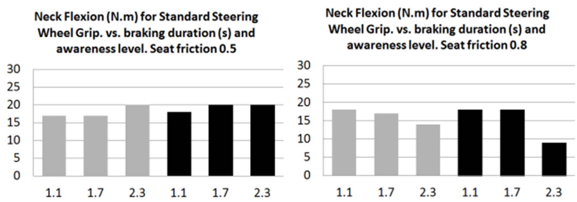

Figure 23. Neck Flexion for Standard Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

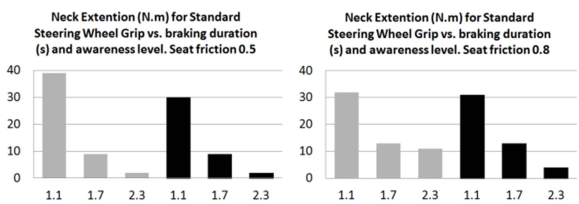

Figure 24. Neck Extension for Standard Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

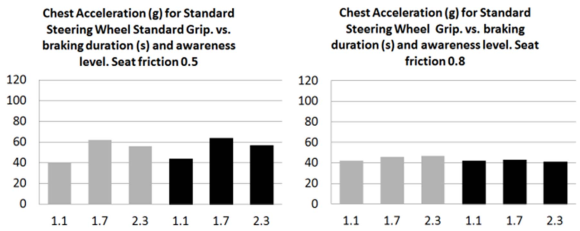

Figure 25. Chest Acceleration for Standard Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

Discussion for the standard 2 hand grip stance

Considering the chest acceleration values from *Figure **25***, it can be observed that the injury values are comparable within a given friction and pre-braking duration value. They are also in the same order of magnitude, between 41g and 64g.

Looking at ***Figure 25*** it can be observed that the maximum chest deceleration values are below 64g, when the braking duration equals 1.7s, i.e. 64g for the 30ms reflex delay and 62g for the 120ms reflex delay one.

Considering *Figure **6***, which is the solar plexus' forward motion, it can be observed that the longer the braking duration, the closer the thorax is to the steering wheel, hence interacts with the airbag sooner.

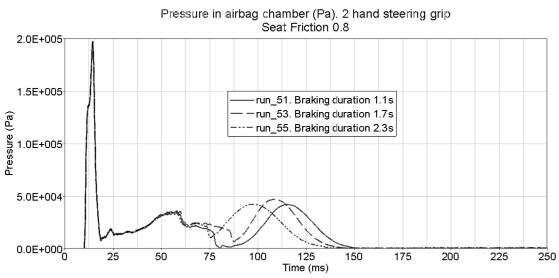

Figure 26. Airbag pressures for a 2 hand steering grip and seat friction of 0.8.

This is illustrated by the airbag pressures (Figure 26) showing the burst-out phase (15ms) followed by the membrane loading phase (from 75ms) which is starting earlier the closer the occupant sits relative to the restraint system.

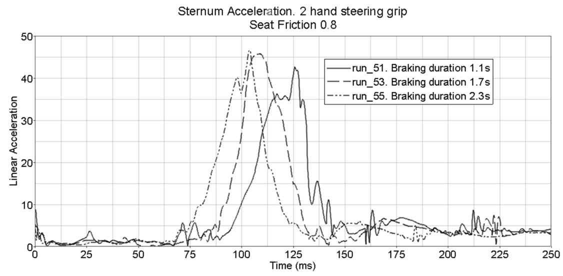

Figure 27. Sternum acceleration for a 2 hand steering grip and seat friction of 0.8.

The delay in the restraint system occupant loading is illustrated by the timing of the chest injuries, especially the chest to steering wheel interactions as illustrated in *Figure 27*.

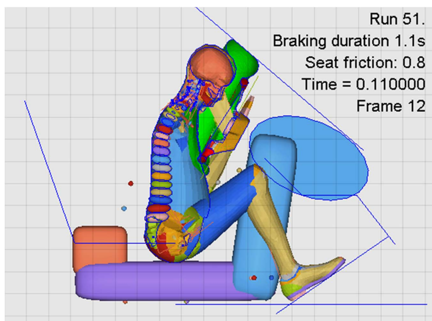

Figure 28. Run51. Start of interaction between chest and steering wheel at time 110ms

The interaction between the chest and the steering wheel can be observed and correlated to the increased chest acceleration starting at time 110ms. This is illustrated in Figure 28, where the occupant's thorax contacts the steering wheel in a 25mph wall impact prior to a 1.1s pre-braking phase.

It must also be noted that in the model, the steering wheel is mounted to a rigid bracket, with no steering column collapse possible. Consequently, the chest acceleration values quoted in this study are comparative values and not absolute ones.

It can be observed from Figure 20 to Figure 25 that contacting the airbag earlier does not generally increase the occupant's injury levels.

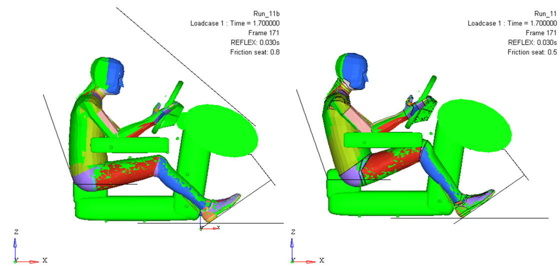

Figure 29. Comparison of occupant kinematics for seat friction 0.5 left, 0.8 right (30ms and 120ms awareness displayed in blue and green respectively). Pre-braking duration of 1.7s.

Looking at Figure 29, it can be also observed that the knees have not yet contacted the dashboard at a time 1.7s before the subsequent impact occurs, compared to a braking duration of 2.3s (*Figure **8*** and *Figure **9***). As a consequence, more mass will be accelerated, hence more energy transferred into the airbag/ steering wheel assembly. This is suggesting that the braking duration is influencing the occupant's kinematics in the subsequent crash scenario. A longer braking duration (2.3s) would mainly cause a rotational torso momentum in the crash phase because the knees are already in contact with the knee bolster at the time of impact, while a smaller braking duration (1.1s and 1.7s) would allow a legs and torso translation followed by a rotation. As a consequence, this will influence the restraint system ride down performance.

Overall, it can be noted that all the injury values do not vary significantly between a motor reflex delay of 30ms and 120ms, as results are comparable in magnitude in Figure 21 to Figure 25, considering the same seat friction parameter. This suggests that a "very aware" and "aware" occupant will withstand comparable levels of injuries on a secondary impact after an unexpected 1g pre-braking.

In all cases the occupant is, after an unexpected pre-braking phase, aligned with the airbag system before the subsequent impact occurs. As a consequence, in this safety scenario and configuration, it can be seen that for a standard 2 hand grip stance the system analysed in this study provides a good level of protection, bearing in mind that the airbag utilised meets OoP1 and OoP2 for a 5th percentile female as well as for a 50th percentile human model.

Considering all the variables (seat friction, reflex delay and braking duration) in this injury study, it can be concluded that the active human model is, in a 2 hand steering wheel grip, very stable in all conditions and that its injury responses are plausible.

Results for the mobile phone stance

Following the kinematics study, the occupants' injuries are calculated up to a pre-braking duration of 1.1s, as it is judged that afterwards the occupant will miss the airbag, as illustrated in Figure 30 and Figure 31.

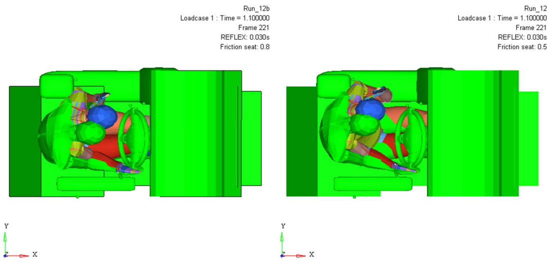

Figure 30. Comparison of occupant kinematics for seat friction 0.5 left, 0.8 right (30ms and 120ms awareness displayed in blue and green respectively). Pre-braking duration of 1.1s.

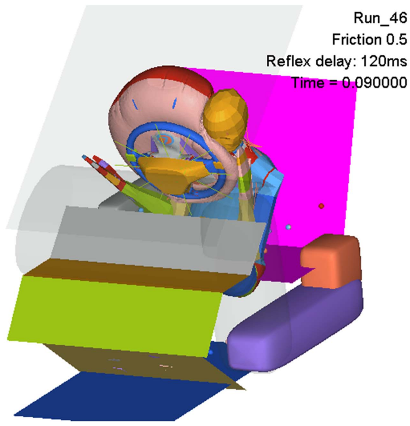

Figure 31. Impact with steering wheel at 90ms. Friction 0.5, Delay reflex 120ms.

Injuries are plotted in *Figure **32*** to *Figure **37***, focussing on cases with a seat friction coefficient of 0.5 and 0.8.

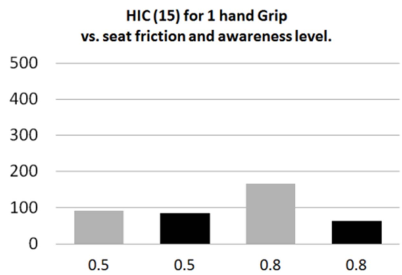

Figure 32. HIC (15) for 1 hand Steering Wheel Grip vs. seat friction. Reflex 30ms (light), 120ms (dark).

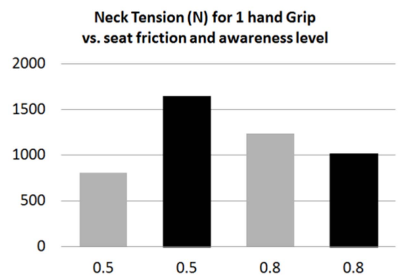

Figure 33. Neck Tension for 1 hand Steering Wheel Grip vs. seat friction. Reflex 30ms (light), 120ms (dark).

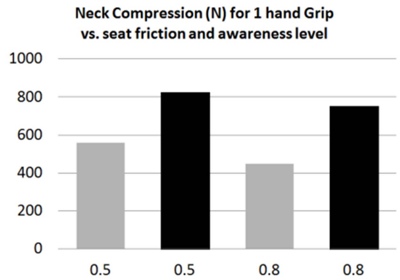

Figure 34. Neck Compression for 1 hand Steering Wheel Grip vs. seat friction. Reflex 30ms (light), 120ms (dark).

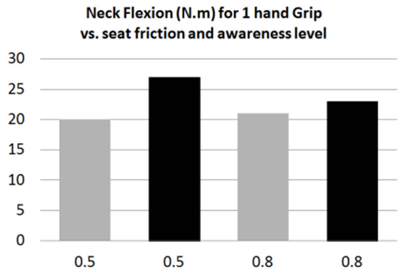

Figure 35. Neck Flexion for 1 hand Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

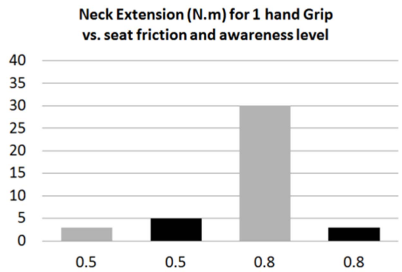

Figure 36. Neck Extension for 1 hand Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

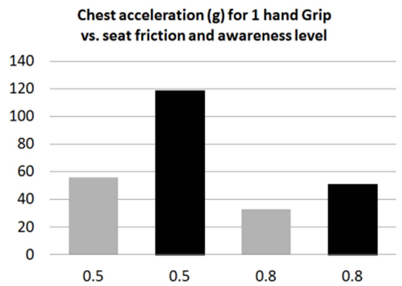

Figure 37. Chest Acceleration for 1 hand Steering Wheel Grip vs. braking duration. Reflex 30ms (light), 120ms (dark).

It can be seen that for a seat friction value of 0.5 that the reflex delay has a greater influence on the injury levels, as the posture of the occupant is away from the airbag zone of influence (Figure 30).

Observing the occupant position at 1.1s from Figure 14 and Figure 15, it can be noted that the occupant relationship relative to the airbag and steering wheel assembly is less favourable to protect the driver before the airbag triggers than in the case of Figure 8 and Figure 9.
In a 1 hand steering wheel grip, the torso and the head are in line with the lateral steering wheel rim, which as a consequence leads to considerably higher chest acceleration (119g), as illustrated in Figure 31. It has to be noted that in all the models, the steering wheel is mounted to a rigid bracket, with no steering column collapse possible. As a consequence, the values quoted are comparative values and not absolute ones.

It has to be can be noted that head injury criteria as well as the Nij (Neck Injury Criteria) values met their legal limit in all cases. This suggests that the airbag adequately protects the occupant's head, but not sufficiently to stop the thorax hitting the steering wheel rim.

For a friction level of 0.8, results suggest that there is not a clear injury level pattern between the 2 levels of reflex delays. This maybe be caused by the fact that the occupant movement is a forward and lateral motion which causes a different interaction with the airbag than what it is designed to do, i.e. protecting for a forward motion. Nevertheless, in this study, for a friction level of 0.8, injury values are all under the legal requirements.

Overall, it seems that seats with higher friction tend to keep the unbelted occupants using a 1 hand steering wheel grip more aligned with the airbag.

Considering all the variables (seat friction, reflex delay and braking duration) in this injury study, it can be concluded that the active human model is, in a 1 hand steering wheel grip, very stable in all conditions and that its injury responses are also plausible.

CONCLUSIONS

The study has initially correlated the Madymo Active Human Model to sled tests involving volunteers wearing a lap-belt and then successfully applied it in an active safety scenario. This scenario involved an unexpected vehicle pre-braking phase of 1g with an unbelted occupant followed by a subsequent 25mph rigid wall impact.
Overall, the study concludes that the Madymo Active Human Model used in this research provides believable kinematics and injury response behaviours. This model is very stable and has responded in a plausible manner when numerous variables, like seat friction, reflex delay and braking duration, were introduced.

The research has suggested that, within the active safety scenario investigated, the occupant's kinematics depend on the seat friction coefficient, arms' kinematics and the level of awareness.
By and large, it has been observed that for a reflex delayed response of less than 120ms that chest, neck and head injuries values for gripping the steering wheel with 2 hands were comparable for a given value of seat friction. Alternatively, occupants with 1 hand on the steering wheel (holding a mobile phone for example) were out of the airbag deployment zone in this research scenario after 1.1s of extreme braking regardless of their state of awareness and seat friction value.

FURTHER WORK

This next step of this study would be to perform the same investigation with a more defined vehicle interior including refined seat as well as adding a collapsible steering column in order to explore restraint system design in active safety scenarios.

The kinematics study could also in the future be replicated with a FCW scenario which would then generated occupant neck and legs bracing behaviour. This study would be possible when a new Active Human model includes these needed leg, spine and arms bracing features.

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Probabilistic and Holistic Vehicle States Prediction with Enhanced Driver Model and Application to Smart Cruise Control Systems

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Paper Number 13-0090

ABSTRACT

This paper presents a probabilistic vehicle states prediction algorithm by using multi-sensor fusion. The system inputs come in two main varieties: 1) vehicle sensor signal, such as steering angle, longitudinal velocity, longitudinal acceleration and yaw rate and 2) vision sensor signal, such as curvature, slope and distance to lane mark. From these inputs, the algorithm presents the time series prediction of future vehicle states and the corresponding covariance matrixes for the pre-defined future time horizon.

The probabilistic states prediction algorithm consists of two sequential parts. The first part is the estimation part which contains a vehicle filter which estimates current vehicle states and a road filter which approximates the road geometry. The second part is prediction part which consists of a path following model generating future desired yaw rate which acts as a virtual measurement and a vehicle predictor which predicts future vehicle states by maximum likelihood filtering method.

The proposed algorithm has been investigated via test data based closed loop simulation with Smart Cruise Control (SCC) system. Compared to two kind of existing path prediction methods; a fixed yaw rate assumption based method and a lane keeping assumption based method, it has been shown that the states prediction performance can be significantly enhanced by the proposed prediction algorithm. And this enhancement of prediction performance led to capabilities improvement of driver assistance functions of SCC by providing accurate predictions about the future driving environment.

INTRODUCTION

Recently, numerous Advanced Driver Assistant Systems (ADAS) have been developed and commercialized for the driver's safety and handling enhancement. A smart cruise control (SCC) system which maintains the safe distance from the preceding vehicle has been introduced to the market and next-generation SCC which can assist driver in obstacle avoidance situation is in progress. And a lane keeping assistance system (LKAS) which prevents an unintended lane departure and guide a vehicle into the lane boundary have been developed. Such systems have been identified to enhance road safety effectively through numerous field tests [1]. In those systems, a reliable prediction for the ego-vehicle's future states should be available for threat assessment and decision-making functions.

The conventional driver assistant systems introduced in the market predict the vehicle's future path based on a fixed circular motion assumption, or a fixed steering angle assumption [3], [4]. However, this method is not sufficient to ensure a correct assignment of the vehicle's future path [2]. The inadequacy of the conventional path prediction method causes wrong threat assessment or wrong decision-making in the corresponding driver assistant system.

Subsequently, some modifications have been suggested. One approach combines a fuzzy rule and finite-state machines to capture all possible driving maneuver sequences [24]. However, this approach has been evaluated only for turn maneuvers. Another approach classifies the maneuver type from current vehicle information such as turn light, brake pedal, etc. and predicts the future path by building various situation models [21]. However, this approach has not been evaluated for dynamic maneuver situation (e.g. lane change).

As the various sensors have been introduced to vehicles, some additional information such as lane marking, GPS based map data have been taken into account. As a part of such effort, the vision sensors, which can detect lanes, are utilized for driving path prediction based on lane trackers [10]. Furthermore, during recent years, digital map contribution toward road geometry estimation is broadly proposed [2], [11]. However, path prediction method which is fully dependent on road geometry still brings a number of problems when the vehicle's motion and the road geometry do not coincide (e.g., lane change or overtake situation) or the road information do not exact.

In short, the vehicle motion based path prediction method is not suitable for a long term prediction because of divergence of prediction error. And the road geometry based path prediction method might not perform well in dynamic maneuvering situations such as lane change or overtake driving. Consequently, two information, the

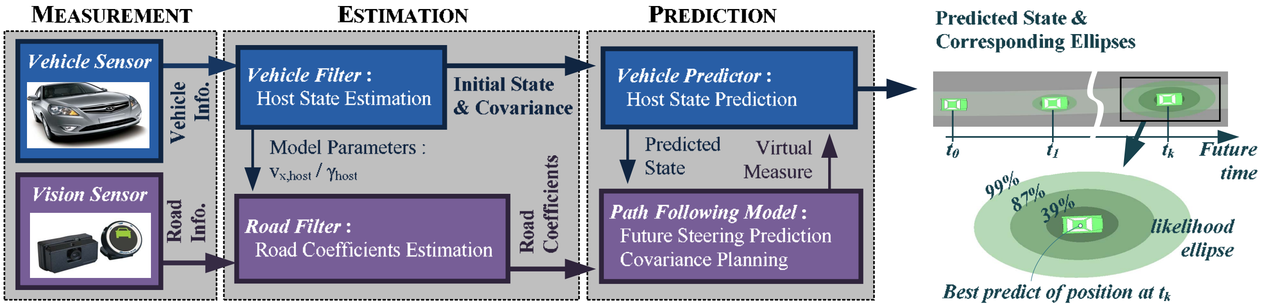


Figure1. Architecture of a probabilistic and holistic states prediction

vehicle states and the road, should be fused properly and reasonably to make the most out of relative merits of each measure.

To satisfy this requirement of information fusion, there are few approaches to propose fusion method and describe its validity. One study proposed independent-parallel two predictions, current dynamics based and road geometry based, and a weighted manner combining method [2]. In this method, it gives more weight to the current dynamics based prediction at the beginning and reduces the weight in a linear sense. However, there is no mathematical description about this linear sense weighting fusion strategy. Other approaches which learns motion patterns by building a motion database have been presented [22], [23]. This method, however, has the drawback that many trajectories have to be stored in large databases and accessed online. Lin et al. [25] presented an approach using numerical integration of a linearized two degree-of-freedom vehicle handling model. However, it assumes constant steering wheel angle and highway speeds (80 km/h). Tsogas et al. [26] has defined various maneuver states and proposed a transition model from one maneuver to another by a state diagram. And Zong et al. [27] combine an Artificial Neural Network (ANN) and a Hidden Markov chain Model (HMM) in their integrated model to identify the driving intention and predict the maneuvering behavior of the driver. In these situation-classification based approaches, there are problems that every complicate situation cannot be predefined.

From a number of literature reviews, main concern in vehicle prediction area at the moment can be summarized as a reliable and reasonable sensor-fusion method for the path prediction. To the authors' knowledge, in addition to this requirement of sensor-fusion, two more requirements have to be concerned. One is that the real time evaluation of prediction error. When the prediction algorithm is utilized in driver risk monitoring function of various Advanced Driver Assistance Systems (ADAS), the evaluation of prediction uncertainty is essential to guarantee the performance of the assistance system. This cannot take place by existing methods because of their deterministic prediction process. And the other is the extension of size of predicted states. Only just future position, so called 'future path', is not sufficient enough to define the actual risk of the vehicle. Therefore more elements such as yaw angle, yaw rate, longitudinal velocity and acceleration, etc. have to be predicted reliably.

To satisfy these requirements of sensor-fusion, states extension and uncertainty evaluation, a sensor fusion based probabilistic prediction method for holistic vehicle states is developed and proposed in this manuscript. The main idea of this study is that a prediction problem can be solved as a multi-stage of optimal estimation problem if we consider the road geometry as the measurement, as the future road geometry is exactly same with the current road geometry.

The algorithm consists of two sequential parts. The first part is the estimation part which contains a vehicle filter which estimates current vehicle states and a road filter which approximates the road geometry. The second part is prediction part which consists of a path following model generating future desired yaw rate which acts as a virtual measurement and a vehicle predictor which predicts future vehicle states by maximum likelihood filtering method.

The proposed algorithm has been investigated via closed-loop simulation with Smart Cruise Control systems. Compared to existing methods, it has been shown that the states prediction performance can be significantly enhanced by the proposed prediction algorithm and this enhancement of prediction performance led to capabilities improvement of driver assistance functions of ADAS by providing accurate predictions about the future driving environment.

PROBABILISTIC STATES PREDICTION

A probabilistic states prediction algorithm presents the quasi-best predicts of ego-vehicle's potential position and corresponding likely ellipses which are covering some given finite time horizon.

The system inputs come in two main varieties: 1) vehicle sensor signal, such as steering angle, longitudinal velocity, longitudinal acceleration and yaw rate and 2) vision sensor signal, such as curvature, slope and distance to lane mark. From these inputs, the proposed algorithm produces a time-series of predicts for vehicle position and corresponding likely ellipses.

Fig. 1 depicts the procedures of a probabilistic states prediction. As shown in the figure, the overall structure of this algorithm consists of 2 parts. The first part is the estimation part which contains a vehicle filter which estimates current vehicle states and a road filter which approximates road geometry. The second part is prediction part which consists of a path following model generating future desired yaw rate which acts as a virtual measurement and a vehicle predictor which predicts future vehicle states by maximum likelihood filtering method.

Estimation

In the estimation part, the vehicle's current dynamic states and the road geometry are estimated. The yaw acceleration and the longitudinal acceleration are very important factors to improve the prediction reliability than conventional method. However, the value of yaw acceleration is very difficult or expensive to measure directly. This value can be successfully estimated in real-time using measurements such as the steering angle, the yaw rate, the longitudinal velocity and the longitudinal acceleration which are available from existing vehicle sensors. And in an approximation of the road geometry, the road geometry is approximated as a 2nd order polynomials in present vehicle coordinate. In this approximation, the coefficients of polynomials can be calculated from road curvature, road slope and vehicle's lateral distance from the road center line and these values can be measured directly by an equipped vision sensor.

Vehicle Filter The Kalman filter is used to estimate present vehicle states such as longitudinal velocity, yaw rate, longitudinal acceleration and yaw acceleration from the vehicle sensor signals such as steering angle, yaw rate, longitudinal velocity and longitudinal acceleration under the assumption of the Gaussian white noise. As aforementioned, the state vector x is defined as following in order to represent the driver's intention and the vehicle's planar behavior:

$$x = [v \quad \gamma \quad a \quad \dot{\gamma}]^T \tag{1}$$

where v is the longitudinal velocity, γ is the yaw rate, a is the longitudinal acceleration and $\dot{\gamma}$ is the yaw acceleration. The measurement vector is defined as following to reflect the available sensor information.

$$z = [v \quad \gamma \quad a \quad \delta_f]^T \tag{2}$$

where δ_f is the front wheel steering angle. Assuming that the time derivatives of the longitudinal acceleration and the yaw acceleration can be considered as the process noise, the process model and measurement model are given by following form:

$$x[k+1] = F[k]\cdot x[k] + w[k] \tag{3}$$

$$z[k] = Hx[k] + v[k] \tag{4}$$

where

$$F = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & h_{42} & 0 & h_{44} \end{bmatrix}$$

$$h_{42} = \frac{2l_f^2 C_f + 2l_r^2 C_r}{2l_f C_f v} \qquad h_{44} = \frac{I_z}{2l_f C_f}$$

where Δt is the sampling time which taken as 0.1 second in this study, I_z is the yaw moment of inertia, C_f and C_r are the front and rear wheel cornering stiffness, respectively and l_f and l_r are the distances from vehicle's center of gravity to front and rear axles. Two elements in 4th row of measurement matrix are determined from the bicycle model which is most well-known lateral vehicle dynamics model. The process noise is assumed to be a white noise with associated covariance matrix, *W*. The measurement noise is also assumed to be a white noise with associated covariance, *V*. Note that measurement model, *H*, is time varying because there exist longitudinal velocity in the element of the matrix. Therefore, it should be re-calculated at each time step. With above process and measurement model, vehicle states are recursively estimated by using the Kalman filter which is a sequence of time and measurement update steps as following specific equations:

Time update

$$\begin{aligned} \bar{x}[k] &= F\cdot\hat{x}[k-1] \\ M[k] &= F\cdot P[k-1]\cdot F^T + W \end{aligned} \tag{5}$$

Measurement update

$$\begin{aligned} \hat{x}[k] &= \bar{x}[k] + K[k]\cdot\left(z[k] - H[k]\bar{x}[k]\right) \\ K[k] &= M[k]H[k]^T\cdot\left(H[k]M[k]H[k]^T + V\right)^{-1} \\ P[k|k] &= \left(I - K[k]H[k]\right)\cdot M[k] \end{aligned} \tag{6}$$

Road Filter Road geometry is the key factor effecting on driver's maneuverings, especially on steering behavior. Therefore, in this section, the method to describe the forward road geometry using the measurement of the vision sensor is discussed. As the first step of the description, the road geometry is defined in current vehicle body coordinate and approximated as the 2nd order polynomials. And secondly, its coefficients are estimated reclusively from the vision sensor measurements and prior estimate of vehicle states.

It is common practice to describe the forward road geometry by a 2nd order polynomial [7]. The relation between the host vehicle and the road center line can be described by two factors. One is a relative lateral position, e_y, and the other is a relative heading angle, e_θ. This is depicted in Fig. 7. With these two factors, the road geometry, which has the curvature radius *R*, can be approximated as following [6]:

$$\begin{aligned} y_r &= \frac{1}{2R}x^2 - \tan e_\theta\cdot x - e_y \\ &\equiv a_2\cdot x^2 + a_1\cdot x + a_0 \end{aligned} \tag{7}$$

where x is the down range distance and y_r is the lateral position of the corresponding road center in current body coordinates. As the vehicle drives with velocity v and yaw rate γ, the coefficients describing the road geometry change according to the motion of the vehicle. The discrete-time process model of the road geometry coefficients can be written in the following state-space form. Details of process modeling will be described in section B.1.

$$x_r[k+1] = F_r[k]x_r[k] + G_r u_r[k] + w_r[k] \quad (8)$$

where

$$x_r = \begin{bmatrix} a_2 \\ a_1 \\ a_0 \end{bmatrix} \quad u_r = \gamma \qquad F_r = \begin{bmatrix} 1 & 0 & 0 \\ 2v\Delta t & 1 & 0 \\ 0 & v\Delta t & 1 \end{bmatrix} \quad G_r = \begin{bmatrix} 0 \\ -\Delta t \\ 0 \end{bmatrix}$$

A subscript '*r*' is used to denote '*of road geometry states*'. The vision sensor provides full information of road state vector. Likewise with the vehicle states estimation, the Kalman filter is used for the estimation of road geometry coefficients. Note that the process model F_r is time varying because there exist longitudinal velocity in the element of the matrix. Therefore, it should be re-calculated at each time step by using the best estimate results of the vehicle filter. The yaw rate which is the system input of road geometry system model also uses the best estimate result of the vehicle filter. Hence the covariance of the process noise should be well-defined so that can represent the effect of the estimate error of the vehicle filter. As the result, road geometry coefficients are recursively estimated by using the Kalman filter which is a sequence of time and measurement update steps as following specific equations:

Time update

$$\begin{aligned} \bar{x}_r[k] &= F_r[k-1]\cdot\hat{x}_r[k-1] + G_r u_r[k-1] \\ M_r[k] &= F_r[k-1]\cdot P_r[k-1]\cdot F_r[k-1]^T + W_r \end{aligned} \quad (9)$$

Measurement update

$$\begin{aligned} \hat{x}_r[k] &= \bar{x}_r[k] + K_r[k]\cdot\left(z_r[k] - H_r\bar{x}_r[k]\right) \\ K_r[k] &= M_r[k]H_r^T\cdot\left(H_rM_r[k]H_r^T + V_r\right)^{-1} \\ P_r[k] &= \left(I - K_r[k]H_r\right)\cdot M_r[k] \end{aligned} \quad (10)$$

Prediction

In the part of prediction, it is assumed that the driver may maintain current behavior in the near future and keep the lane in the end. To implement this assumption, a path following model and a vehicle state predictor keep interacting with each other during the prediction processing. A path following model generates the desired yaw rate which consists of error state feedback term and road curvature feedforward term. The feedback and feedforward law is determined properly so that it can represent the human driver's yaw behavior on the road. And a vehicle state predictor predicts the vehicle's future potential position and its error covariance by linearized Kalman filtering with using the path following model based desired yaw rate as the virtual measurement.

Path Following Model The objective of a path following model is to develop a yaw control system for human-like lane keeping. To achieve this goal, it is useful to utilize a dynamic model in which the state variables are in terms of position and orientation error with respect to the road. The error state is defined in term of fixed coordinate under the assumption of traveling with constant longitudinal velocity on a road of constant radius. Note that the error state is defined in inertial fixed coordinates not in body-fixed moving coordinates. By using the definition of the road geometry in section A.2, the position error can be defined as

$$e_y = p_y - \left\{a_2\cdot p_x^2 + a_1\cdot p_x + a_0 + w_{road}\cdot N(current\,lane)\right\} \quad (11)$$

where w_{road} is the width of the road lane and N is the adjusting integer to represent the current lane. For example, if the vehicle changes the lane to the left one, N has the value of minus one. Under the small slip angle assumption, the time derivative of the position error can be defined as

$$\begin{aligned} \dot{e}_y &= \frac{d}{dt}(p_y) - (2a_2\cdot p_x + a_1)\cdot\frac{d}{dt}(p_x) \\ &\cong v\sin\theta - (2a_2\cdot p_x + a_1)\cdot v\cos\theta \end{aligned} \quad (12)$$

where v is the longitudinal velocity and θ is the orientation. The orientation error and its time derivative can be defined as

$$e_\theta = \theta - \tan^{-1}(2a_2\cdot p_x + a_1) \quad (13)$$

$$\begin{aligned} \dot{e}_\theta &= \dot{\theta} - \frac{d}{dt}\left\{\tan^{-1}(2a_2\cdot p_x + a_1)\right\} \\ &= \gamma - \frac{1}{1+(2a_2\cdot p_x + a_1)^2}\cdot\frac{d}{dt}(2a_2\cdot p_x + a_1) \\ &= \gamma - \frac{1}{1+(2a_2\cdot p_x + a_1)^2}(2a_2)\cdot\frac{d}{dt}(p_x) \\ &= \gamma - \frac{2a_2}{1+(2a_2\cdot p_x + a_1)^2}\cdot(v\cos\theta) \end{aligned} \quad (14)$$

Under the small road slope and small error assumptions, above time derivatives of error states can be simplified as follows:

$$\begin{aligned} \dot{e}_y &= v\sin\theta - (2a_2\cdot p_x + a_1)\cdot v\cos\theta \\ &= v\cos\theta\cdot\left\{\tan\theta - (2a_2\cdot p_x + a_1)\right\} \\ &\cong v\cos\theta\cdot e_\theta \end{aligned} \quad (15)$$

$$\begin{aligned} \dot{e}_\theta &= \gamma - \frac{2a_2}{1+(2a_2\cdot p_x + a_1)^2}\cdot(v\cos\theta) \\ &\cong \gamma - 2a_2\cdot(v\cos\theta) \end{aligned} \quad (16)$$

If the yaw rate dynamics can be approximated as 1st order system which has the desired yaw rate as the system input, the state space model of tracking error variables is given by following equation.

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} e_y \\ e_\theta \\ \gamma \end{bmatrix} &= \begin{bmatrix} 0 & v\cos\theta & 0 \\ 0 & 0 & 1 \\ 0 & 0 & f \end{bmatrix}\cdot\begin{bmatrix} e_y \\ e_\theta \\ \gamma \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -f \end{bmatrix}\gamma_{des} + \begin{bmatrix} 0 \\ -2v\cos\theta \\ 0 \end{bmatrix}a_2 \\ &\equiv F_e\cdot x_e + G_e\cdot\gamma_{des} + G_w\cdot a_2 \end{aligned} \quad (17)$$

We can see that first and second raw of equation describe the road geometry coefficient process model under the assumption of fixed road curvature.

Assume that the human drivers determine the desired yaw rate by state feedback plus a feedforward tem that attempts to compensate for the road curvature as following:

$$\begin{aligned}\gamma_{des} &= -Cx_e + \gamma_{ff} \\ &= -\begin{bmatrix} c_1 & c_2 & c_3 \end{bmatrix} x_e + \gamma_{ff}\end{aligned} \tag{18}$$

Similar to the road curvature, if the feedforward term is constant, the steady state is given by

$$\begin{aligned}\begin{bmatrix} e_y \\ e_\theta \\ \gamma \end{bmatrix}_{ss} &= -\left(F_e - G_e C\right)^{-1} \cdot \left(\begin{bmatrix} 0 \\ 0 \\ -f \end{bmatrix} \gamma_{ff} + \begin{bmatrix} 0 \\ -2v\cos\theta \\ 0 \end{bmatrix} a_2 \right) \\ &= \begin{bmatrix} \frac{1}{c_1}\cdot\left(\gamma_{ff} - 2a_2 v\cos\theta\left(c_3+1\right)\right) \\ 0 \\ 2a_2 v\cos\theta \end{bmatrix}\end{aligned} \tag{19}$$

Hence, we can see that the all error states can be made zero by appropriate choices of feedback gains and feedforward term. For example, the feedback gain can be determined by pole placement which is simulating the human driver's behavior characteristics. Then the feedforward term can be calculated directly from above feedback gain and estimated road curvature by equation (20).

$$\gamma_{ff} = 2a_2 v\cos\theta\left(c_3+1\right) \tag{20}$$

Vehicle Predictor In the prediction of the vehicle's future states, the only measurement available is the road geometry described in current body coordinate. As aforementioned, under the assumption that the driver may maintain current behavior in the near future and keep the lane in the end, the path following model based desired yaw rate is used as the virtual measurement while the prediction process. Consider the future vehicle system as the stochastic, multistage process described as following:

$$x_p[i+1] = f_p\left(x_p[i]\right) + w_p[i], \qquad i = 0,\cdots,N_p - 1 \tag{21}$$

where

$$x_p = \begin{bmatrix} p_{x,p} & p_{y,p} & \theta_p & v_p & \gamma_p & a_p & \dot{\gamma}_p \end{bmatrix}^T$$

$$f_p\left(x_p\right) = x_p + \begin{bmatrix} v_p\cos\theta_p & v_p\sin\theta_p & \gamma_p & a_p & \dot{\gamma}_p & -k_a a_p & -k_{\dot{\gamma}}\dot{\gamma}_p \end{bmatrix}^T \cdot \Delta t$$

where N_p is the length of the pre-defined prediction time horizon and a subscript '*p*' is used to denote '*predictive*'. The longitudinal and yaw acceleration are assumed to be decayed with some time constants.

At each time step, as a noisy measurement of the true future yaw rate, desired yaw rate is evaluated by path following model. Let us suppose the measurement noise is also normal distributed, with zero mean. Hence a predictive measurement is linearly related to the predictive states by

$$\begin{aligned} z_p[i] &= H_p \cdot x_p[i] + v_p[i], \qquad i = 0,\cdots,N_p \\ &\equiv \bar{\gamma}_{des,p}[i] \\ &= -C\cdot\bar{x}_{e,p}[i] + \gamma_{ff,p}[i] \end{aligned} \tag{22}$$

Then the maximum likelihood predict of the future state is given by the following extended Kalman filtering. As an example, a predict procedure at 1st future time step is depicted in Fig. 3-4.

Time update

$$\begin{aligned} \bar{x}_p[i] &= f_p\left(\hat{x}_p[i-1]\right) \\ F_p[i-1] &= \left.\frac{\partial f_p}{\partial x_p}\right|_{x_p=\hat{x}_p[i-1]} \\ M_p[i] &= F_p[i-1]\cdot P_p[i-1]\cdot F_p[i-1]^T + W_p \end{aligned} \tag{23}$$

Measurement update

$$\begin{aligned} \hat{x}_p[i] &= \bar{x}_p[i] + K_p[i]\cdot\left(z_p[i] - H_p\bar{x}_p[i]\right) \\ K_p[i] &= M_p[i]H_p^T\cdot\left(H_p M_p[i] H_p^T + V_p[i]\right)^{-1} \\ P_p[i] &= \left(I - K_p[i]H_p\right)\cdot M_p[i] \end{aligned} \tag{24}$$

Evaluation of Prediction Error Because the proposed prediction algorithm is based on stochastic filtering method, the covariance of prediction error can be evaluated at each time step as shown in equation (24). Furthermore, the 2nd eigenvalue and eigenvectors of the 2nd leading principal minor of P_p determine the likelihood ellipse around predictive position [19]. Using the square root of the eigenvalues as semi-axes, measured along the eigenvectors, we can sketch the 39 percent likelihood ellipse with center at most likely predictive position. The 87 percent likelihood ellipse is two times the size of the 39 percent ellipse in linear dimension and 99 percent is three times. This is depicted in Fig. 7. This analysis is very useful to visualize and compare the prediction performance in the view of accuracy and precision.

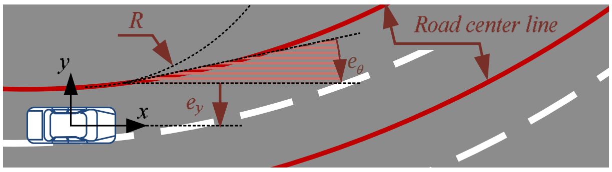


Figure2. Relationship between the host vehicle and the road center line

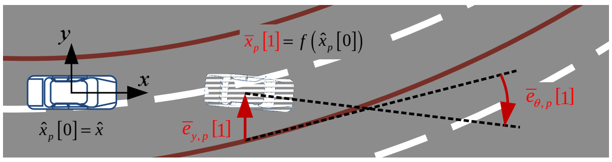


Figure3. Time-update-predicted host vehicle states and the relative error states with respect to road geometry defined on current body coordinate

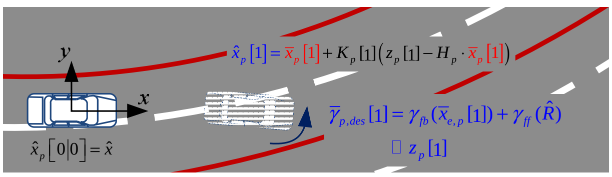


Figure4. Measurement-update-predicted host vehicle states where the predicted desired yaw rate to keep the lane is defined as virtual measurement

TESE DATA BASED CLOSED-LOOP SIMULATION WITH SMART CRUISE CONTROL SYSTEM

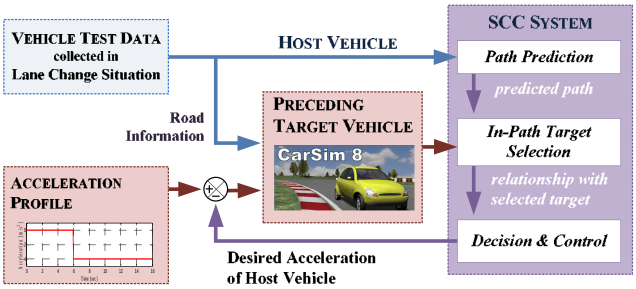
To validate the applicability of the proposed algorithm and to evaluate the performance enhancement induced by the algorithm in perception module of Advanced Driver Assistance System, simulation study has been conducted by using the commercial vehicle software Carsim and Matlab/Simulink. As the objective of the simulation is to investigate the induced performance enhancement of the target selection module in SCC by proposed algorithm compared to conventional methods, a scenario is selected as a lane change driving situation with presence of target vehicle on the new lane. Based on a collected real-road driving data, a driving scenario is re-constructed in computer simulation. The comparisons with the conventional Fixed Yaw Rate Model (FYRM) and Lane Keeping Model (LKM) are presented in this section. FYRM is the model which predicts the vehicle future states under the assumption of fixed current yaw rate and LKM based prediction assumed that the driver may keep the current lane which has no consideration of vehicle states is also applied and compared.

Simulation Environment

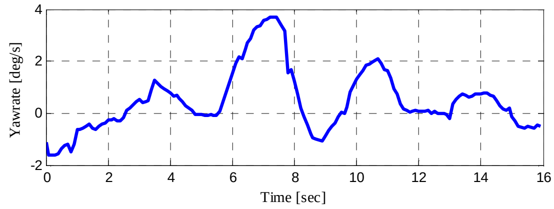
A primary target detection performance was evaluated by a simulation on an asphalt road in lane change driving situation. In the case of the ego-vehicle, a collected test data in lane change situation is applied as open-loop inputs. Since a simulation was conducted to evaluate target detection performance and associated SCC functions, a preceding vehicle which drives on the new lane set to keep constant velocity and start decelerating with deceleration level of 4 m/s^2 after the time that the ego vehicle starts its lane changing. For simulating the closed loop feedback response of the SCC system, the desired longitudinal acceleration command from the SCC system has been applied and added to the preceding vehicle's pre-defined acceleration profile with negative value. This is equivalent with general closed-loop simulation in longitudinal relative behavior between both vehicles.
The description of the simulation is summarized in Fig. 5. As shown in the figure, the host vehicle starts its lane changing at 6 sec. And at the same time, the virtual preceding vehicle on the new lane is set to start decelerating by open-loop acceleration profile as shown in Fig. 5-(g). The perception module of SCC system which is appointed to do path prediction is replaced by each conventional and proposed prediction algorithm and comparative analysis is conducted in the view of the performance of SCC.

Simulation Results

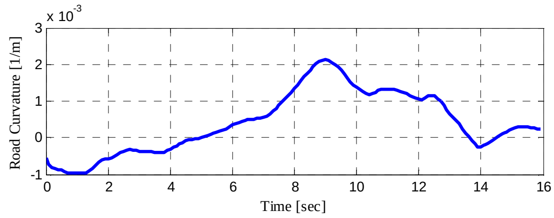
The simulation results are given in Fig. 6-9. The results have shown the some important performance difference and corresponding improvement of safety and convenience functions. In case of the FYRM based simulation which is denoted by dotted blue line, we can see that target loss has



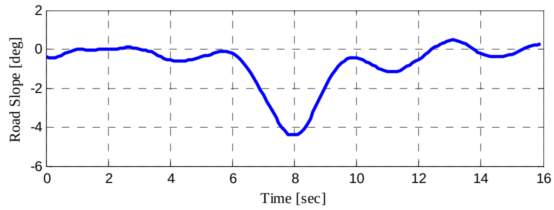
(a) Structure of the simulation



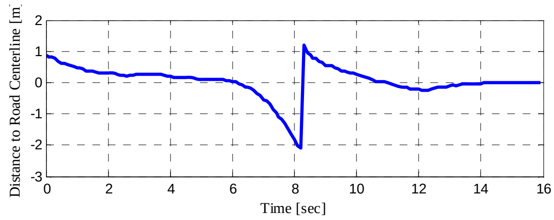
(b) Test data of the yaw rate of the host vehicle



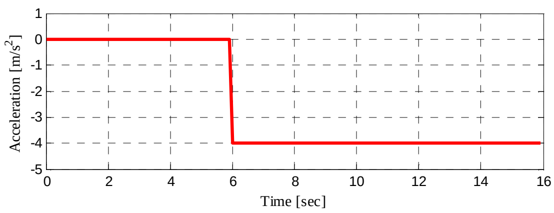
(c) Test Data of the road curvature



(d) Test Data of the relative road slope to host vehicle



(e) Test Data of the distance to road centerline of host vehicle



(f) Open-loop acceleration profile of preceding vehicle

Figure5. Closed loop simulation environment based on real vehicle test data

occurred frequently as shown in Fig. 8-(b). The first target loss is caused by the miss-predicted path which veers off to the lane change direction as depicted in Fig. 6-(b). And the second target loss is caused by miss-predicted path which veers off to the lane correct direction which is depicted in Fig. 7-(b). Because of these two times of target loss, SCC system with FYRM based prediction module cannot maintain the safe distance from the preceding vehicle and used oddly severe deceleration which may cause the driver inconvenience.

In LKM based case, there is no target loss but target detecting delay problem has been shown. The reason of this delay problem is that the LKM based path prediction method does not change the pursuing lane until the center of mass cross the boundary of the lane. Because of this target detecting delay problem, SCC system started deceleration late and used oddly severe deceleration to maintain the safety distance and cause the driver inconvenience. Note that in case of LKM, prediction error covariance cannot be evaluated because of non-realistic trust in path following model.

At last, in cased of the proposed algorithm, the primary target vehicle which drives on the new lane is detected without target loss and detecting delay. As a result, the starting point of longitudinal deceleration of the ego-vehicle is moved forward almost 1 second compared to LKM based SCC system and retain more safety distance with smaller level of deceleration compared to FYRM based SCC system. Therefore it is shown that the control performance of the SCC system is enhanced in two important viewpoints; the longitudinal collision control safety and the convenience of the driver.

CONCLUSION

A novel method for the prediction of the ego-vehicle's states has been presented. This algorithm is developed to predict the ego-vehicle's states accurately and improve the performance of perception and risk assessment module in Advanced Driver Assistance Systems (ADAS). The probabilistic states prediction algorithm consists of two sequential parts. The first part is the estimation part which contains a vehicle filter which estimates current vehicle states and a road filter which approximates the road geometry. The second part is prediction part which consists of a path following model generating future desired yaw rate which acts as a virtual measurement and a vehicle predictor which predicts future vehicle states by maximum likelihood filtering method.

The proposed algorithm has been investigated via vehicle tests data based closed loop simulation with perception module of SCC. It has been shown that the states prediction performance can be significantly enhanced by the proposed prediction algorithm, especially in curve entry, exit and lane change driving situations and the enhancement of prediction performance led to capabilities improvement of driver assistance functions of ADAS by providing accurate predictions about the future driving environment.

The proposed algorithm can be utilized in perception modules of advanced driver assistance systems such as Emergency Driving Support (EDS) system, Advanced Emergency Braking System (AEBS), side-crash prevention system, Advanced Lane Change Assistance (ALCA) system and expected to enhance the vehicle safety in various driving situations

ACKNOWLEDGMENT

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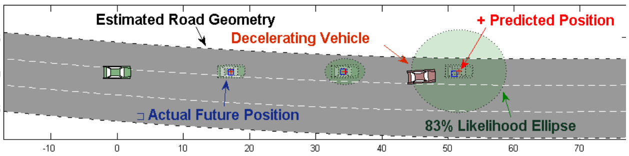
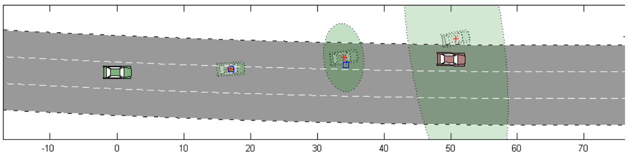
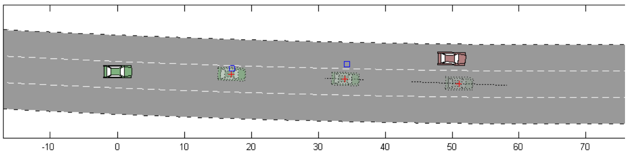


(a) Proposed method based prediction

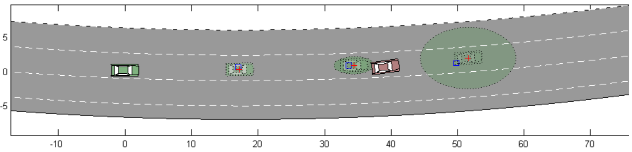


(b) Fixed Yaw Rate Model based prediction

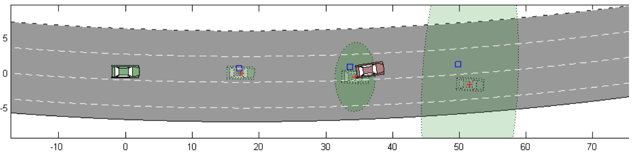


(c) Lane Keeping Model based prediction

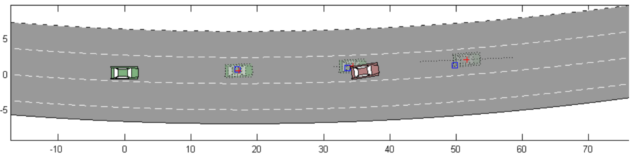
Figure. 6 Comparison of prediction results for 3 second of future time between the conventional and proposed method while lane change driving



(a) Proposed method based prediction

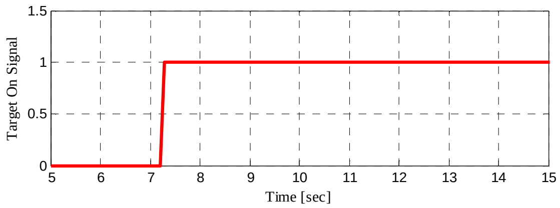


(b) Fixed Yaw Rate Model based prediction

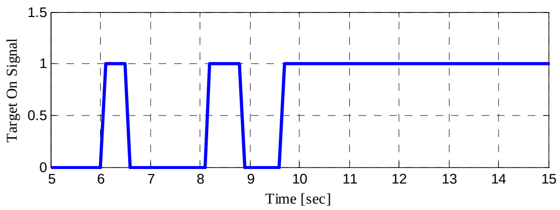


(c) Lane Keeping Model based prediction

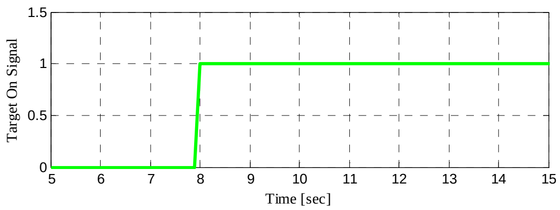
Figure. 7 Comparison of prediction results for 3 second of future time between the conventional and proposed method while lane correct driving



(a) Target detecting signal with proposed algorithm

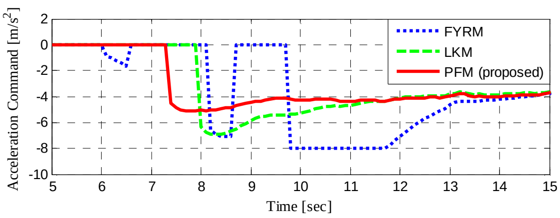


(b) Target detecting signal with fixed yaw rate model

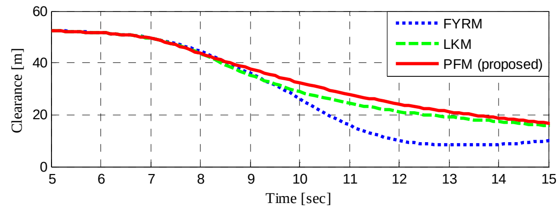


(c) Target detecting signal with lane keeping model

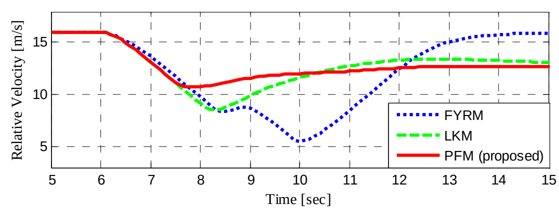
Figure. 8 Comparison of the target detecting performance



(e) Desired acceleration command of each method



(e) Clearance of each method



(e) Relative velocity of each method

Figure. 9 Comparison of the control results with SCC

An Investigation of Suitable Timing for a Vision-based Rearward Approaching Vehicle Notification System

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ABSTRACT

Systems for detecting and notifying drivers of vehicles in adjacent lanes have attracted considerable interest as a means of reducing driver workload which tends to increase when changing lanes. This paper presents the results of a study that investigated the relationship between the timing for issuing a notification about a vehicle detected in an adjacent lane and the related effect on drivers' trust in the system. The purpose of this study is to improve the perceived effect and value of such notification systems. Subjective evaluations were conducted using an experimental vehicle and a vehicle detection method employing a rear-mounted camera. Based on the evaluation results obtained, an investigation was made of a suitable timing for a system that notifies drivers about a rearward approaching vehicle when changing lanes.

1. INTRODUCTION

Vehicles equipped with a rear-view camera have become increasingly common in Japan in recent years. In the U.S., the National Highway Traffic Safety Administration (NHTSA) has proposed creating a new rule that would require all vehicles to be equipped with a rear-view camera. These developments suggest that the use of rear-view cameras can be expected to expand in the coming years.

Automobile manufacturers and auto parts makers are currently engaged in vigorous research activities on sensing technologies for use in driving safety support systems (DSSS). In particular, technologies for detecting vehicles in adjacent lanes are being actively researched for the purpose of preventing lane change accidents [1]. In view of this situation, we have developed a vehicle detection method using a single rear-mounted camera with the aim of expanding the application of DSSS to a wider range of vehicles [2].

The interface of DSSS that incorporate some type of vehicle detection technology is also being studied [3][4]. These examples of research studies dealt with certain issues inherent in vehicle detection systems. For example, consider a situation where the error rate for vehicle detection is extremely low. In this case, drivers may overly rely on the system, resulting in a greater possibility of an accident in the event a vehicle detection error actually occurs. Conversely, if vehicle detection errors occur repeatedly, drivers may not trust the system, with the result that the system

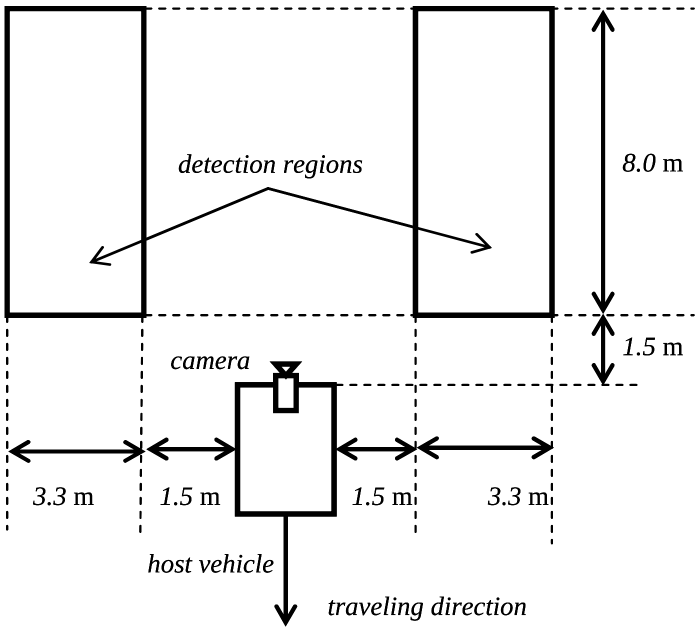

Figure 1. Position of detection regions

cannot deliver its intended benefits. Therefore, these interface studies were undertaken to examine how changing the way the detection results are presented to the driver might affect the level of drivers' trust in vehicle detection systems. However, the timing for presenting a notification to encourage drivers to be careful has not been thoroughly discussed in the literature yet.

It is assumed that the perceived effect of a system for notifying drivers of a rearward approaching vehicle will vary depending on the timing for issuing such a notification. That is because the relative positions of the host vehicle and rearward vehicle will differ depending on when a notification is issued.

In this study, a notification system was constructed by using the method developed previously for detecting a rearward approaching vehicle [2]. The timing for issuing a notification was varied in experiments to investigate how it might affect drivers' perception of the effect of the system.

2. RELATED WORK

The Japan Automobile Research Institute reported the results of a study on the behavioral characteristics of drivers at the time of changing lanes [5]. Based on their analysis of the time-to-collision (TTC) with a rearward approaching vehicle, they found that drivers changed lanes regardless of the distance between the two vehicles provided that TTC was at least 8 s and that they refrained from changing lanes when TTC was 4 s or shorter. When TTC was between 4 and 8 s, the results were mixed, with some drivers changing lanes while others refrained from doing so. These findings suggest that TTC of between 4 to 8 s represents a period when the driver's workload is especially heightened. Accordingly, in this study we investigated the effects of setting the timing for issuing a notification in this period.

3. VEHICLE DETECTION METHOD

As illustrated in Fig. 1, the vehicle detection method [2] developed previously judges whether or not a vehicle is present in either of two detection regions predefined behind the host vehicle. If a vehicle is detected, its relative velocity can be estimated and used to vary the timing of the notification so as to match the TTC at that moment. Further details of the detection method are given in reference [2].

4. PROBLEM FORMULATION

The purpose of this study therefore was to investigate the effects of the notification timing in the period when the driver's workload for changing lanes is assumed to be especially high as mentioned in section 2. With the vehicle detection method [2] used in this study, the detection regions were defined as far as a distance of 9.5 m from the rear of the host vehicle, as shown in Fig. 1. Accordingly, vehicles at a rearward distance of up to approximately 9 m were the target of detection. With these detection regions, a notification sound can be issued at a maximum TTC of around 6 s when the relative velocity between the host vehicle and a rearward approaching vehicle is 5 km/h. The notification timing of the system used in this study was therefore varied in a TTC interval from 4 to 6 s. The effects of varying the notification timing in this interval on the participating drivers' subjective evaluations of the timing were investigated experimentally.

5. EXPERIMENT

5.1 Experimental Configurations

An experimental vehicle was setup and used in all of the experiments conducted in this study. The configuration of the experimental vehicle is shown in Fig. 2. The images captured with a camera mounted at the rear of the vehicle were fed into a PC. The computer activated the vehicle detection method [2] to detect any vehicles that were actually approaching

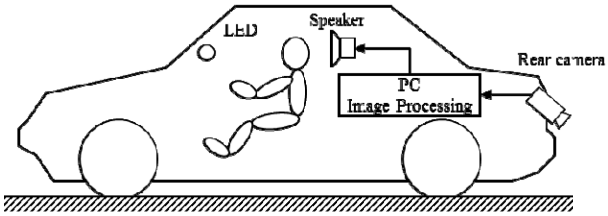

Figure2. Configuration of experimental vehicle

(a)LED Off (b)LED On

Figure3. Indicator to start lane change maneuver

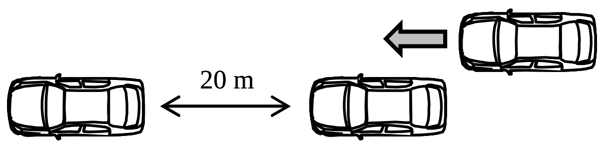

Figure4. Vehicle locations

from behind the experimental vehicle. When an approaching vehicle was detected, a notification sound was emitted from a speaker installed in the cabin. The "*notify.wav*" notification sound provided in Windows was used for that purpose. A light-emitting diode (LED) installed on the windshield served as an indicator for instructing the driver to start a lane change maneuver (Fig. 3).

In addition to the experimental vehicle and the rearward approaching vehicle, a vehicle was also positioned in front of the experimental vehicle, making a total of three vehicles altogether. This configuration simulated a vehicle following situation on a straight road in the evaluation experiments (Fig. 4).

5.2 Experimental Scenario and Driver's Task

The experiments simulated a vehicle following situation as illustrated in Fig. 4, with one lead vehicle positioned ahead of the experimental vehicle driven by a participant in the experiment. From the perspectives of safety and reproducibility, both the experimental vehicle and the lead vehicle were stationary and only the rearward approaching vehicle was moving. The participants were instructed to focus on the preceding vehicle in this experimental scenario that simulated a situation of following a vehicle ahead at a speed of approximately 50 km/h.

As shown in Fig. 3(b), the LED was illuminated at a certain given timing. The participants were instructed to begin a lane change maneuver the moment they noticed the illuminated LED. They were instructed to confirm that the condition around the experimental vehicle was safe, just as they would do in ordinary driving, and to turn the steering wheel if they judged that a lane change could be executed. If they judged that a lane change was impossible, they were told not to do anything.

5.3 Experimental Method

As described in section 4, the experimental configuration that provided a relative velocity of 5 km/h between the experimental vehicle and the rearward approaching vehicle allowed the notification sound to be issued at a maximum TTC of around 6 s. Table 1 shows the relationship between TTC and the distance between the two vehicles when their relative velocity was 5 km/h. Based on this relationship, the TTC was varied at 0.5 s increments between 4.0-6.0 s. The participants were asked to give their subjective evaluations of a total of five TTC notification timing patterns. The parameters of the vehicle detection program were pre-adjusted so that the notification sound would be issued according to the predetermined TTC.

A test engineer monitored the images captured by the rear camera and illuminated the LED upon confirming that the rearward approaching vehicle had reached the position of the TTC specified for a particular experiment. The participants were instructed to start lane changing when the LED was illuminated, if they thought it was appropriate to change lanes. On the other hand, if they thought that changing lanes was inappropriate then they should not do anything. To simulate a real lane changing situation, it would have been favored to leave the decision to start lane changing to the participant himself. However, this would make it difficult to assure the repeatability of the experiment. It is thought that the proposed method would induced a natural behavior of the participants

Table1. Relationship between TTC and inter-vehicle distance

TTC[s]	4.0	4.5	5.0	5.5	6.0
Distance[m]	5.55	6.25	6.94	7.64	8.33

5.4 Procedure

The experiments were conducted according to the following procedure.

- The purpose of this study was explained to the participants in advance, and their written informed consent was obtained before beginning the experiments.
- After confirming that the participants understood the purpose of the study, they were informed that the experiments simulated a situation of executing a lane change while driving straight ahead.
- As a practice exercise, all the participants experienced the illumination of the LED and the issuing of the notification sound at a TTC timing of

5.0 s.

● In the actual experiments, the LED was illuminated and the notification sound was issued while varying the TTC in 0.5 s increments between 4.0-6.0 s. The participants gave their subjective evaluations of each of the five notification sound timing patterns, which constituted one set of experiments.

● Three sets of experiments were conducted in total, and the scores were averaged to determine the final evaluation results of each participant. It should be noted that TTC was varied at random within each set of experiments.

The participants were 23 drivers (21 men, average age of 40.3 years; 2 women, average age of 38.5 years) who ordinarily drive a vehicle to commute to work or for some other purpose.

5.5 Evaluation Method

The purpose of the experiments was to evaluate how the participants perceived the notification sound issued by the system while inducing the start of a lane change maneuver within a TTC range of 4.0-6.0 s. The participants subjectively evaluated the timing of the notification sound on a five-point scale. In making their subjective evaluations, the participants were told to confirm that the condition around the experimental vehicle was safe, just as they would do when changing lanes in ordinary driving, as explained earlier in section 5.2. That was done by visually confirming the presence of a rearward approaching vehicle seen in the outside mirror or in the rear-view mirror in the cabin.

The evaluation criteria of each point score are explained below.

● 1 (early): The notification sound is annoying. In this case, the participant perceives that a lane change is possible because there is a sufficiently safe distance between the host vehicle and the rearward approaching vehicle.

● 2 (slightly early): a rating between 1 and 3.

● 3 (adequate): The participant perceives that the timing of the notification sound is effective. The participant perceives that the timing of the notification sound, when the distance between the host vehicle and the rearward approaching vehicle is close, is helpful in deciding to refrain from changing lanes.

● 4 (slightly late): a rating between 3 and 5.

● 5 (late): The participant perceives that the timing of the notification sound is not very helpful in deciding to refrain from changing lanes because the rearward approaching vehicle is already too close to the host vehicle at this point.

6. RESULTS

6.1 Overall Evaluation Results

The evaluation results of the 23 participants are shown in box plots in Fig. 5. The horizontal axis is the TTC in seconds and vertical axis shows the subjective evaluation ratings for each TTC. As an overall tendency, it is observed that the subjective evaluations of the participants change according to the TTC. Many of the participants evaluated the notification timing at TTC = 4.0 s as being “late” or “slightly late”. However, there were two participants who evaluated this notification timing as being “adequate”. These results will be discussed further in the section 6.2.

For notification timings at TTC = 4.5 s or 5.0 s, many of the participants tended to respond that the timing was “slightly late” or “adequate”. No participant evaluated the timing at TTC = 4.5 s as being “slightly early” or “early”, but four of the 23 participants responded that the timing at TTC = 5.0 s was “slightly early”.

Many of the participants responded that the notification timing at TTC = 5.5 s was the most “adequate” of the five timing patterns used in the experiments. Moreover, the evaluation results for this notification timing showed the smallest dispersion. Compared with the timing at TTC = 5.5 s, the number of participants who responded that the timing at TTC = 6.0 s was “slightly early” or “early” increased, and the dispersion of the evaluation results also increased accordingly.

6.2 Individual Evaluation Results

Figure 6 shows the subjective evaluation results for all of the 23 participants. The horizontal axis is the

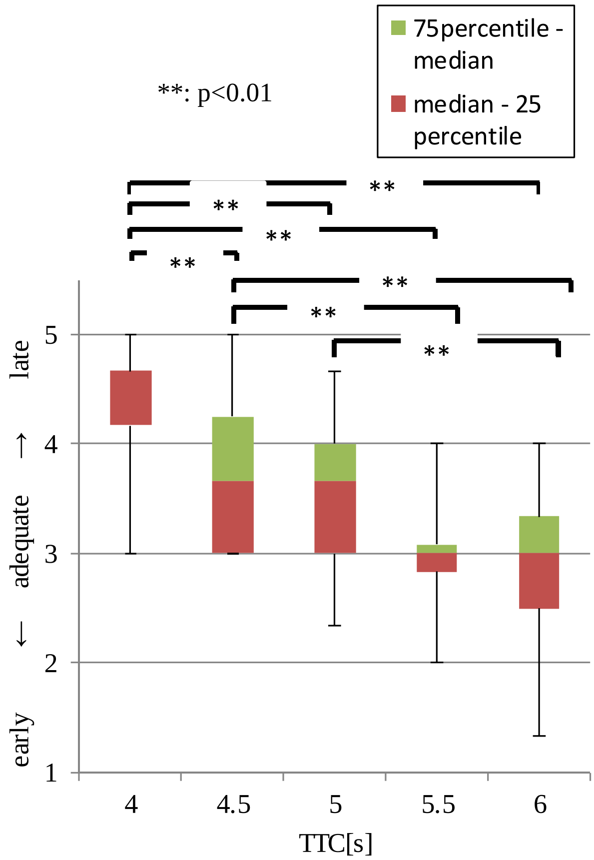

Figure5. Distribution of subjective evaluation results

TTC and the vertical axis indicates the evaluation ratings for each TTC. The evaluation results of each individual participant are shown as an approximation line. Two of the 23 participants responded that all of the notification timings were “adequate” regardless of the TTC. It is inferred that these two participants thought the system was effective simply because it issued a notification sound, irrespective of the TTC with the rearward approaching vehicle. On the other hand, it is observed that the subjective evaluation results for the other 21 participants change in relation to the TTC. All of these participants tended to evaluate the timing as being “late” when the TCC value was small and increasingly to respond that the timing was “early” as the TTC value became larger.

7. DISCUSSION

First of all, we will discuss the overall evaluation results presented in section 6.1. As shown in Fig. 5, the five TTC patterns used in the experiments were paired to create ten combinations of patterns altogether. Of the ten pairs of patterns, the subjective evaluation results for eight combinations showed a significant difference ($p<0.01$). The two pairs of patterns that did not show a significant difference were the combinations of 4.5 s and 5.0 s and 5.5 s and 6.0 s. The only common point between these combinations was that the time difference was just 0.5 s. Presumably, the reason for that is because all of the participants were included in this comparison. An evaluation of the results for the individual participants will be discussed later.

Next, we will consider the subjective evaluation results for each TTC. For the notification timing at TTC = 4.0 s, the participants’ evaluations were more concentrated at “ late” or “slightly late” compared with the results for the other timing patterns. The

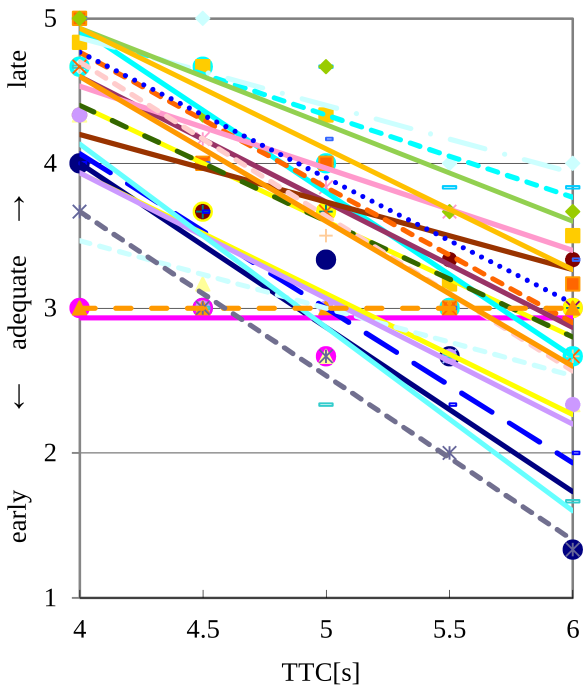

Figure6. Subjective evaluation results for all participants

The symbols in the figure plot the subjective evaluation results of the participants. The same symbols and colors are used for the same participant in the TTC range from 4.0 to 6.0 s. The straight lines of the same colors as the symbols are the approximation lines of the evaluation results of those participants.

Japan Automobile Research Institute reported that in their study no drivers changed lanes when TTC was 4.0 s or less [5]. In a similar way, the participants in the present study evaluated the notification at that timing as being “late”. For that reason, a significant difference occurred between TTC = 4.0 s and TTC = 4.5 s, though the two timings differed by only 0.5 s.

For notification timings at TTC = 4.5 s and 5.0 s, many of the participants’ evaluations were distributed between “slightly late” and “adequate”. The dispersion of the results for these timings was larger and fewer participants responded “adequate” compared with the subjective evaluation results for TTC = 5.5 s and 6.0 s. We will next consider the subjective evaluation results for TTC = 5.5 s and 6.0 s. The Japan Automobile Research Institute reported that the mean and standard deviation of the time needed for drivers to change lanes was 5.58 ±1.29 s and that drivers estimated the relative positions of the two vehicles before executing a lane change maneuver based on the relative speed between their vehicle and the rearward approaching vehicle [5]. Accordingly, the number of participants in the present study who evaluated notification timings of 5.5 s and 6.0 s as being “adequate” probably increased because many of them judged that the risk of a collision with the rearward approaching vehicle would be high if they actually changed lanes. On the other hand, the number of participants who evaluated the notification timings at TTC = 4.5 s and 5.0 s as being “slightly late” presumably increased because many of them judged that the risk of a collision was clearly more definite.

We will now consider the evaluation results for the individual participants presented in section 6.2. All of the pairs of the five TTC patterns that were subjectively evaluated in this study showed a significant difference ($p<0.05$). This suggests that if TTC varies by 0.5 s, drivers’ evaluation of the effect of a notification system based on the timing of the notification will probably vary.

Next, we will also analyze the approximation lines of the evaluation results of the 21 participants mentioned earlier. The mean and variance of the slope of the approximation lines of these 21 participants were -0.61 and 0.031, respectively, indicating that the individual difference was small. On the other hand, the mean and variance of the intercept were 7.04 and 1.03, respectively. Compared with the slope, an individual difference is evident ($p<0.05$). This presumably suggests that the participants had different expectations of the notification timing of the system when changing lanes. A close observation of the approximation lines in Fig. 6 reveals that they could be divided into two groups. In one group the values of the approximation lines at TTC = 4.0 s are 4.2 or higher and in the other group they are less than 4.2. A significant difference ($p<0.01$) is thus observed between the two groups. At least for the 23 participants who participated in the present study, it can be inferred that their subjective evaluation of the effect of the notification system would probably improve provided that two patterns of notification timings were provided as system options to choose from.

8. CONCLUSION

This study examined the change in drivers' subjective evaluation of a notification system for a rearward approaching vehicle when the timing for issuing a notification was varied to match the time-to-collision (TTC) with the approaching vehicle. The following conclusions can be drawn from the experimental results.

(1) The experimental results confirmed that the subjective evaluations of the participating drivers changed when the notification timing was varied to match TTC.

(2) Notification timings at TTC = 5.5 s and 6.0 s were evaluated highly by the participants, based on the time needed to execute a lane change and the estimated speed and position of the rearward approaching vehicle.

(3) The results showed there were individual differences among the participants regarding the effect of the notification timing, but that such differences could be grouped together into two major groups.

The experiments conducted in this study were carried out under a limited driving environment. In order to analyze more thoroughly the timing for issuing a notification by a rearward vehicle detection system, it will be necessary to conduct experiments in real-world driving environments. Because of the parameters of the vehicle detection technology used in this study, experiments were conducted only at TTC values up to 6.0 s. In future work, it will also be necessary to conduct evaluation experiments using larger TTC values.

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Research into Evaluation Method for Pedestrian Pre-collision System

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ABSTRACT

Researchers in Japan, Europe, and the United States of America are investigating ways to help reduce pedestrian accidents. Methods of how to evaluate the pre-collision systems (PCS) for pedestrians are being considered with the goal of global dissemination and enhancement of the performance. This paper analyzes accident and near-miss incident data and proposes evaluation conditions for a pedestrian PCS. The development of a test apparatus for assessing the performance of the pedestrian PCS under the proposed evaluation conditions is also described.

First, accident data was analyzed to determine the evaluation scenario. The frequency of each combination of vehicle and pedestrian behavior in pedestrian accidents was investigated. According to the analysis results, the most frequent accident scenario was a pedestrian crossing a road while a vehicle goes straight ahead. This scenario was selected for the evaluation. After collating the accident data in terms of pedestrian age, the research focused on two accident patterns: one involving elderly pedestrians and one involving children. The accident scenario evaluation conditions include the position lateral to the vehicle at which the pedestrian appears, the walking direction, vehicle speed, and the like. These specific conditions were set by analyzing pedestrian accident data and near-miss incident data. For accidents involving elderly pedestrians, two evaluation conditions were set: crossing from the left during daytime and crossing from the right at night. For children, the evaluation conditions featured a child emerging suddenly from behind a parked vehicle.

Next, a pedestrian dummy capable of evaluating the PCS based on these conditions were developed. The pedestrian dummy must be compatible with the use of automotive millimeter wave radar or cameras by the PCS under the evaluation conditions. For a PCS that uses millimeter wave radar, a pedestrian dummy will be required to have low reflection intensity, a capability to reflect radar waves from the entire body, and a walking motion. For a PCS that uses cameras, a dummy must be capable of simulating a human body with both arm and leg movement. To achieve these requirements, the skeletons of the pedestrian dummy were manufactured from vinyl chloride pipes. The reflection intensity was adjusted by winding a metal tape around the entire body of the dummy. A walking mechanism which moves both the arms and the legs was provided from above the pedestrian dummy.

The developed dummy successfully simulated a pedestrian by achieving a reflection intensity which is virtually identical to an actual pedestrian, and a highly realistic walking motion. Furthermore, the test apparatus was developed to assess the PCS under the proposed evaluation conditions.

INTRODUCTION

Nearly half of global traffic accident fatalities are vulnerable road users [1]. In Japan, although the number of traffic accident fatalities has continued to decline, this trend is slower for pedestrians. Consequently, the proportion of pedestrians within the total number of traffic accident fatalities is increasing. Since 2008, the proportion of fatal accidents involving pedestrians has risen to approximately 30%, which is the highest proportion of the various crash types [2].

For this reason, pre-collision systems (PCS) capable of detecting pedestrians are being researched and developed as a type of active safety system. One such PCS for pedestrian detection that is already in use helps to alleviate pedestrian injury or helps to avoid a collision by warning the driver when a collision is imminent and then providing braking assistance or even automatically braking the vehicle if the driver does not brake after the warning.

With the goal of facilitating more widespread use and enhancing the functions of this type of PCS for pedestrian detection, methods of evaluating the performance of these systems are currently being researched, including standards and assessments [3]. In this research, standard test methods and ways of estimating system effectiveness is considered. For example, Ando et al. used a lateral-facing static pedestrian dummy to calculate the collision avoidance rate at various vehicle speeds [4]. This data was then analyzed to calculate the fatality reduction effect based on the vehicle speed in accident data. Although this effect was proposed as a method to evaluate system performance, this research has issues that remain to be resolved. To implement this evaluation method, the evaluation conditions based on the accident data must be defined. However, the research does not discuss the relationship between the tests and actual accidents. Furthermore, the dummy used in the evaluation was not capable of sufficiently simulating the characteristics of a pedestrian.

Consequently, this paper describes evaluation conditions based on pedestrian accident analysis using pedestrian accident data and near-miss incident data. It also summarizes the requirements and the development of pedestrian dummy and a test apparatus for use in this research.

DEFINITION OF EVALUATION CONDITIONS

Pedestrian Accident Analysis

The pedestrian accident evaluation pattern was defined based on the pedestrian accident data. The data source was traffic accidents in 2009 compiled by the Institute of Traffic Accident Research and Data Analysis (ITARDA) in Japan. The relevant data was extracted based on two requirements: the first party in the accident must be a vehicle, and the second party must be a pedestrian.

Accident pattern analysis First, to extract the accident patterns for evaluation, the frequency of each combination of vehicles and pedestrian behavior was investigated. Figure 1 shows the percentage of fatalities caused by each combination. Accident scenarios involving the vehicle going straight ahead while a pedestrian crosses the road account for approximately 60% of all pedestrian fatalities. This was selected as the accident pattern to be evaluated.

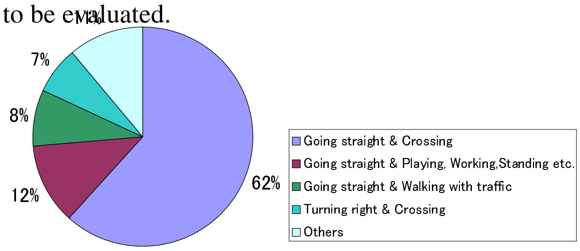


Fig1. Percentage of fatalities for each combination of driver and pedestrian behavior.
(Source :compiled by ITARDA)

Age-based analysis of pedestrian accidents Since the behavior of how to cross the road differs according to age, the age of the relevant pedestrians in the accident data was analyzed. Figures 2 and 3 show the number of traffic accident fatalities and casualties per 100,000 pedestrians in each age group. This data indicates that pedestrians aged 65 or older accounted for approximately 70% of fatalities. In contrast, children aged 12 or under accounted for approximately 30% of casualties. It was concluded that elderly pedestrians and children are more susceptible to involvement in traffic accidents. Therefore, the characteristics of these accidents and the road-crossing behavior of these age groups were analyzed more in detail to identify the test conditions.

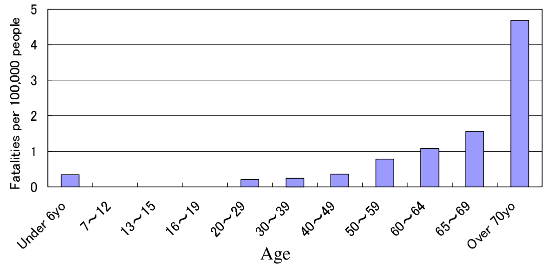


Fig.2 Fatalities according to age
(Source :compiled by ITARDA)

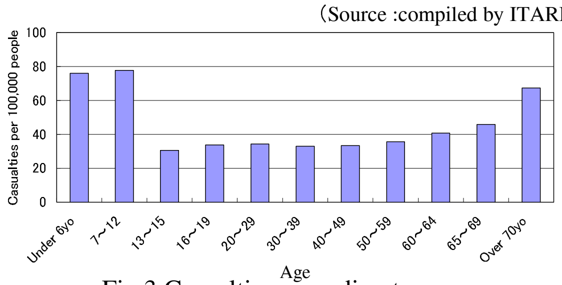


Fig.3 Casualties according to age
(Source :compiled by ITARDA)

Definition of Evaluation Conditions

Within the process from pedestrian detection to system operation, the evaluation conditions were considered based on an accident pattern in which a vehicle goes straight ahead while a pedestrian crosses the road. The following five parameters were set to examine the pedestrian recognition performance of the system and the time from pedestrian detection to collision: (1) the walking direction of the pedestrian and the time of day the accident occurred, (2) the position lateral to the vehicle at which the pedestrian appears (lateral appearance position), (3) the walking speed, (4) the position of the impact at the front of the vehicle, and (5) the vehicle speed. These conditions were investigated for both elderly pedestrians and children.

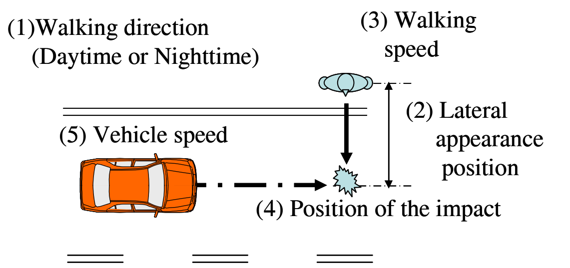


Fig.4 Pedestrian accident parameters

Walking direction of pedestrian and time of day the accident occurred The time accidents occurred has been described in previous research [5]. Elderly pedestrians are more likely to be involved in an accident between 10 and 11 o'clock in the morning (daytime) and between 5 and 7 o'clock in the evening (nighttime). Accidents involving children are more likely to occur between 7 and 8 o'clock in the morning and between 4 and 5 o'clock in the afternoon. The relationship between the time of the accident and the walking direction shows a virtually equal proportion between left and right during the daytime. However, at night, 70% of accidents occur when the pedestrian crosses the road from the right. This is because drivers are slower to see objects further away on the right at night than objects on the left.

Lateral appearance position The major factor affecting the pedestrian lateral appearance position is whether the driver's view of the pedestrian is blocked by a parked vehicle or other objects (this is referred as visual influence). Matsuura investigated the visual influence of parked vehicles and other objects for various age groups [6]. This research found that the visual influence was low in the case of accidents involving elderly pedestrians. However, it also found that approximately half of accidents involving children aged 12 or under involved congestion, stepping out of a vehicle, or a similar condition. Therefore, the research described below evaluated accidents without another object for elderly pedestrians, and accidents with children appearing from behind a parked vehicle.

The pedestrian lateral appearance position can only be defined by examining the situation before the accident risk occurs. However, since accident data is only recorded after the risk occurs, it is not adequate to define the lateral appearance position [7]. Actual images or similar data are the best way of examining the situation before the accident risk occurs. Consequently, this research used the near-miss incident database created by The Society of Automotive Engineers of Japan to analyze the pedestrian lateral appearance position and behavior. The pedestrian data was extracted from the database with the near-miss level set to high. The database identified 58 accident cases that could be grouped into the following categories of pedestrian appearance. The lateral appearance position was examined for each category.

Pedestrian appearing from left:
- Appearance from road shoulder or sidewalk
- Appearance from behind parked vehicle

Pedestrian appearing from right:
- Appearance from median strip or from the right on a single-lane road
- Appearance from behind oncoming vehicle
- Appearance from outside of oncoming lane

Fig.5 Drive recorder data of pedestrian lateral appearance positions

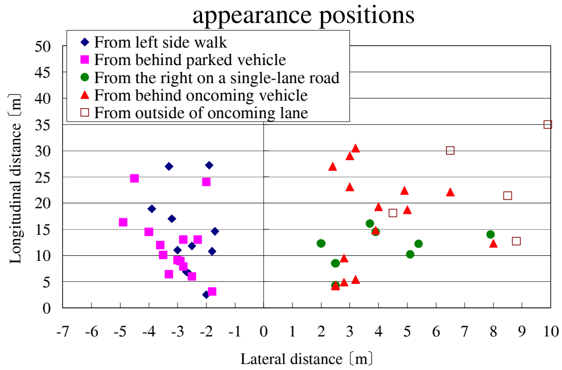


Fig.6 Distribution of pedestrian lateral appearance positions (near-miss data).

Fig.7 Drive recorder data of pedestrian appearance behind parked vehicles.

Figure 5 shows one of the near-miss incidents. The lateral appearance position is defined as the lateral distance from the position at which the whole body of the pedestrian is visible to the center of the vehicle. Figure 6 shows the pedestrian lateral appearance positions identified from the image analysis. The lateral appearance position distribution of pedestrians coming from the road shoulder on the left or from a sidewalk is between 1.9 and 4 meters. The lateral appearance position distribution of pedestrians emerging from behind a parked vehicle on the left is between 2 and 5 meters. The near-miss incident images indicated that pedestrians can be seen further away from the parked vehicles. As a result, the pedestrians were visible further away than the parked vehicle in lateral distance (Figure 7). The positional relationship between the parked vehicle and the pedestrian must be identified to define the evaluation conditions when a parked vehicle is present. Therefore, two distances were examined using the data of pedestrians emerging from behind a parked vehicle: the longitudinal distance from the pedestrian to the parked vehicle, and the lateral distance between the driver's vehicle and the parked vehicle. Figure 8 shows the distance from the pedestrian to the parked vehicle and Figure 9 shows the lateral distance between the driver's vehicle and the parked vehicle. Figure 8 shows that most pedestrians leave a gap of between 1 and 2 meters. Therefore, the median value of 1.5 meters was set as the distance between the pedestrian and the parked vehicle in this research. In the same way, Figure 9 also shows a lateral distance of between 1 and 2 meters between the parked car and the driver's car. The median value of 1.8 meters was set as the evaluation distance in this research.

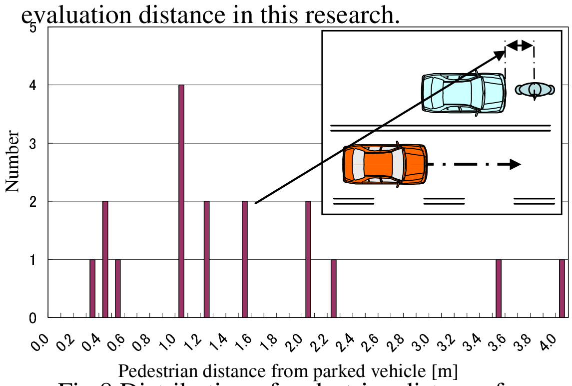


Fig.8 Distribution of pedestrian distance from parked vehicle

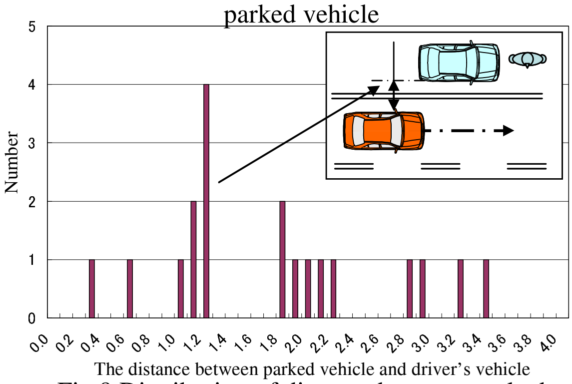


Fig.9 Distribution of distance between parked vehicle and driver's vehicle

Using these results, the lateral appearance position of pedestrians crossing from the road shoulder or sidewalk on the left was set to 3 meters (the median value in the distribution shown in Figure 6). In the case of pedestrians emerging from behind a parked vehicle, the lateral distance between the driver's vehicle and the parked vehicle was set to 1.8 meters, and the distance between the pedestrian and the parked vehicle was set to 1.5 meters.

The lateral appearance position of pedestrians coming from the right was considered separately. Although the lateral appearance position of pedestrians from the median strip or the right of a single-lane road is shorter than other conditions, it was still at least 2 meters. For this reason, the lateral appearance position in these cases is the same or longer than scenarios involving pedestrians coming from the left. Many cases of pedestrians emerging from behind an oncoming vehicle had a lateral appearance position of between 3 and 5 meters. This scenario has a wide distribution because the pedestrian lateral appearance position changes depending on the intersection timing with the oncoming vehicle. Finally, the lateral appearance position of pedestrians coming from the outside of the oncoming lane was between 4.5 and 10 meters. These results indicate that the lateral appearance position of pedestrians crossing from the right is further outward from the driver's vehicle compared to pedestrians crossing from the left. For this reason, it should be possible to evaluate a PCS using pedestrians crossing from the left only. However, an evaluation from the right is required because drivers are slower to see objects further away on the right in accidents at night. After examining the lateral appearance positions of pedestrians coming from the outside of the oncoming lane or emerging from behind an oncoming vehicle, 6 meters was selected as the lateral appearance position for pedestrians crossing from the right (the median value of the distribution of 2 to 10 meters).

Walking speed Walking speed is another factor affecting road crossing behavior. This behavior was investigated for each age group. A comparison between accidents involving adults and children found that most adults were walking normally, but a large proportion of children were running [8]. Consequently, this research used a normal walking speed for elderly pedestrians and running speed for children.

Various research has already investigated walking speed. This research adopted 4 km/h as the normal walking speed for elderly pedestrians, which is the median value defined by Hino et al. [9]. The running speed of children varies greatly according to age. This research set the running speed assuming a 6-year old child. After investigating the running speed of 6-year old children, Sato et al. found that the speed of children increased more slowly than adults and that it requires 3 meters for children in this age group to accelerate to approximately 9 km/h [10]. This value was set as the child running speed.

Impact position at vehicle front Accident data cannot be used to determine the impact position since it includes cases in which the driver braked or steered the vehicle immediately before the collision. This makes it difficult to identify the estimated position of impact prior to the collision. Therefore, published ITARDA reports were examined [11] and the impact position was estimated based on the relationship between the position of the pedestrian when the accident risk occurred and the vehicle speed. Figures 10 and 11 show the impact position frequency in accidents involving pedestrians crossing from the left and right, respectively. The lateral position from the left side of the vehicle is shown as a negative value and the lateral position from the right side of the vehicle is shown as a positive value. The vehicle width was assumed to be 1.8 meters. For both directions, the most frequent impact position was toward the center of the vehicle. However, some impacts occurred further from the center and the overall distribution is wide. Consequently, the center of the vehicle was set as the impact position in this research.

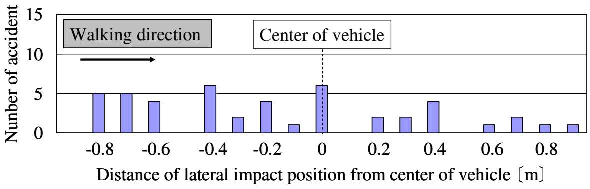


Fig.10 Lateral impact position from left side

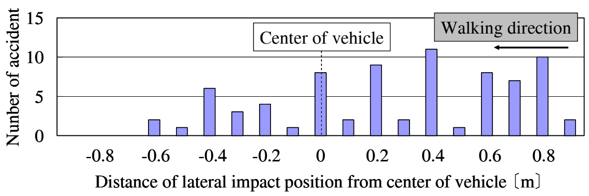


Fig.11 Lateral impact position from right side

Vehicle speed Vehicle speed is an important condition because a vehicle travelling at higher speed will take longer time to slow down, which requires technology to detect pedestrians from further away. In addition, although the time to collision is comparatively longer when the vehicle speed is lower, pedestrians must be detected within a wide angle since the speed difference between the pedestrians and the vehicle is smaller. As a result, PCS evaluation must be carried out at both lower and higher speed conditions.

The accident data from ITARDA were used to investigate the fatality rate and the serious and slight injury rates at each vehicle speed in pedestrian accidents. Figure 12 shows the results.

The rate of fatal accidents increases when the vehicle speed exceeds 30 km/h. The rate of slight injuries falls to 10% or less at 60 km/h as the rate of fatalities and serious injuries increases. For this reason, a speed of between 30 and 60 km/h was selected as the evaluation conditions in this research.

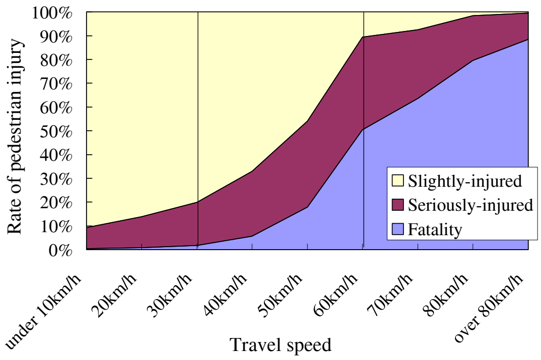
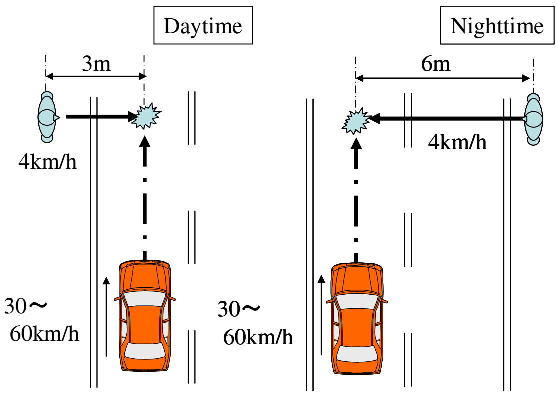


Fig.12 Rate of injury level at each travel speed

（Source :compiled by ITARDA）

Definition of evaluation conditions Figures 13 and 14 show an outline of the evaluation conditions set based on the results described above. Two test patterns were set for elderly pedestrians: crossing the road from the left at daytime and from the right at nighttime. One test pattern was set for children: suddenly emerging from behind a parked vehicle at nighttime. A test pattern involving a child crossing the road from the right was omitted.



(a) From left side (b) From right side

Fig.13 Test patterns for elderly pedestrians

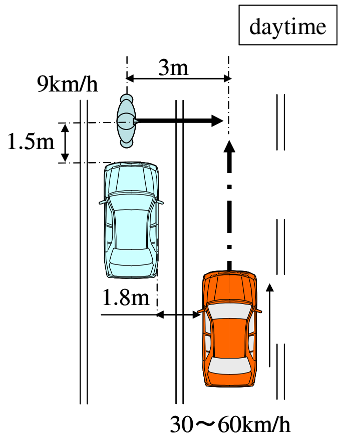


Fig.14 Test pattern for child pedestrians

RESEARCH OF PEDESTRIAN PCS TEST APPARATUS

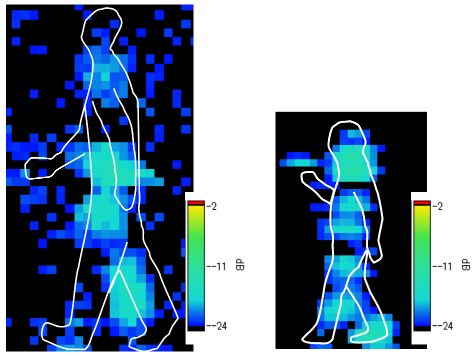
Development of Pedestrian Dummies

As described above, the evaluation conditions were defined by analyzing pedestrian accident data. A pedestrian dummy for a test is required to evaluate the deceleration performance of a PCS under the defined conditions. Since the dummy used will affect the pedestrian recognition performance of the system, the dummy must closely resemble actual pedestrians as viewed by the on-board detection sensors.

Currently, vehicles equipped with a PCS for pedestrian detection use three types of detection method: a stereo camera, a combination of millimeter wave radar and a monocular camera, and a combination of millimeter wave radar and a stereo camera. This section discusses the requirements of pedestrian dummies compatible with millimeter wave radar and cameras, and describes dummies capable of satisfying these requirements. For a preliminary study, an AM50 dummy and a 6-year old pedestrian dummy with precisely defined dimensions were prepared.

Requirements and example dummies compatible with millimeter wave radar detection The reflective characteristics of millimeter wave radar have already been identified in the case of a static human body. A person is approximately 1/100 as reflective as a vehicle [12]. A pedestrian dummy must be capable of simulating the reflective characteristics of a person in terms of how each part of the body reflects millimeter waves and in terms of a human walking motion. First, the sideways reflective characteristics of a midsize adult (AM50) and a 6-year old child were measured to investigate how each part of the body reflects millimeter waves. A 77 GHz millimeter wave radar (the RI76G-01 manufactured by KEYCOM Corporation) was used to measure the radar cross section (RCS) from the side of the human subjects. The height of the millimeter wave radar was set to 650 mm, assuming installation in a vehicle. Figures 15(a) and (b) show the measured results for the AM50 and 6-year old child. The subjects only who agreed with informed consent were attended to the experiment.

Figure 15 shows that radar waves were reflected mainly from the pelvis, torso, knees, and shoulders. This indicates that more radar waves are likely to be reflected from surfaces directly facing the millimeter wave radar. In other words, a dummy must simulate a human physique and be capable of reflecting waves from the entire body to achieve the same reflection distribution.



(a)AM50 (b) 6 years old

Fig.15 Human RCS distribution

Next, two types of reflective characteristics were investigated to examine the effects of walking: a static state with the arms and legs spread out to simulate a walking posture, and the same posture in a moving state. The same 77 GHz millimeter wave radar was used. Figures 16 to 19 show the results (Figures 16 and 17: AM50, Figures 18 and 19: six-year old child). A comparison of the results shows that the reflection intensity in the moving state has a much finer cycle of fluctuation. Previous research also indicated that the reflection intensity fluctuates in accordance with extremely small movements of the body [12]. This is because the radar waves reflected from each part of the body overlap, becoming more intense or canceling each other out. These extremely small movements of the body are not constant and differ from person to person. In Figures 17 and 19, the timing of the drop in the radar wave reflection has a constant cycle. This is due to the interconnected motion of arms and legs during walking, creating a fine fluctuation cycle. These results indicate that walking changes the reflective characteristics. Therefore, a dummy must have movable arms and legs to simulate the millimeter wave radar reflective characteristics of a pedestrian.

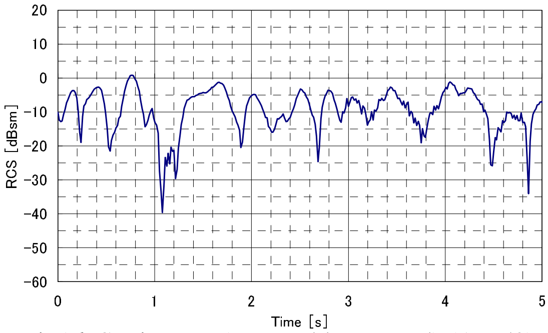


Fig16. Static state (arm and leg spread) (AM50)

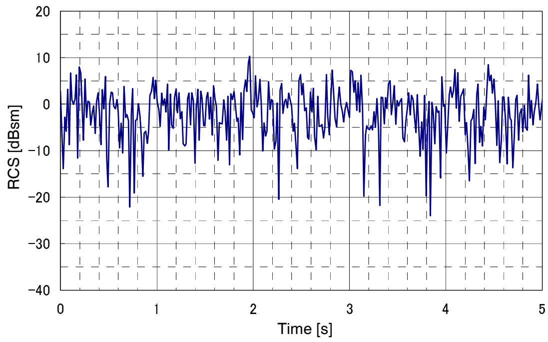


Fig17. Walking state (AM50)

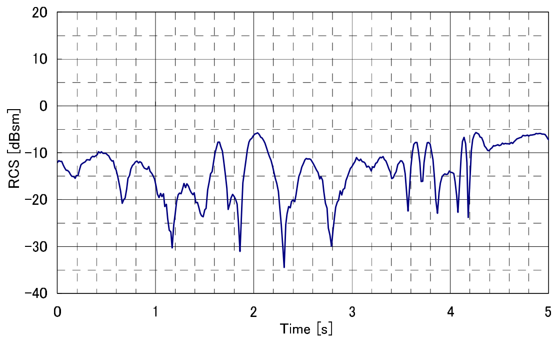


Fig18. Static state (arms and legs spread) (6-year old child).

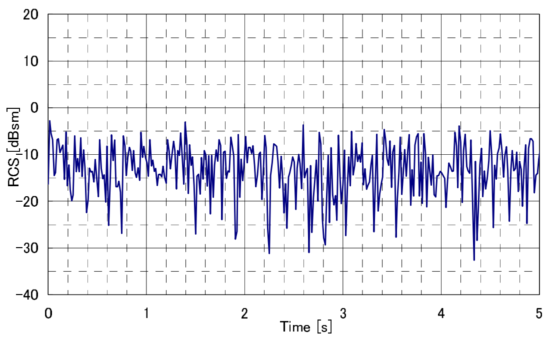


Fig19. Walking state (6-year old child).

In addition, the following requirements for a pedestrian dummy were identified in previous research.

(1) Low reflection intensity

(2)Capability to reflect radar waves from the entire body

(3) Capable of making walking motion

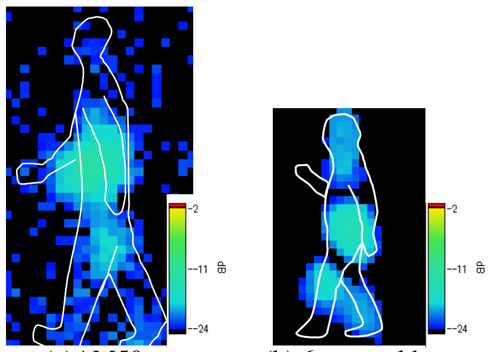
To satisfy these three requirements, the dummy was developed as follows.

- Use vinyl chloride pipes for the dummy skeleton to achieve low reflection, and adjust the position and amount of reflective material on the dummy surface to simulate the reflection intensity to a human.

- Achieve full-body reflection by placing reflective material over the whole of the dummy body.

- Provide a mechanism above the pedestrian dummy (to reduce the effect of the mechanism on the reflection intensity) to simulate arm and leg movement.

Pedestrian dummies that satisfy these requirements were developed specifically as follows. A lifelike sponge body was created that allows reflective material to be attached to the whole body. The reflection intensity was adjusted by winding metallic mesh tape around the surface of the sponge. The same 77 GHz millimeter wave radar measurement apparatus as described above was used to measure the reflection intensity. In the same way as with the measurement with human subjects, two types of evaluation were carried out: an investigation into the RCS distribution from the side, and the fluctuation in reflection in a walking state. Figures 20(a) and (b) show the reflection distribution results for the AM50 dummy and 6-year old child dummy, respectively. Replicating the results with the human subjects, radar waves reflected mainly from the pelvis, torso, knees, and around the shoulders. Figure 21 shows the reflection intensity with a walking AM50 dummy and Figure 22 shows the results for the 6-year old child dummy. The average reflection intensity also replicated the fine fluctuation cycle of the human subjects.



(a)AM50 (b) 6 years old

Fig.20 RCS distribution of pedestrian dummy

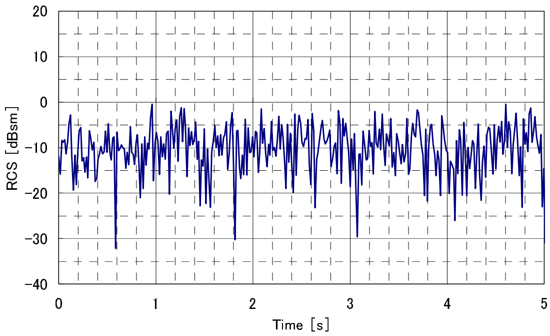


Fig21. Walking state (AM50 dummy)

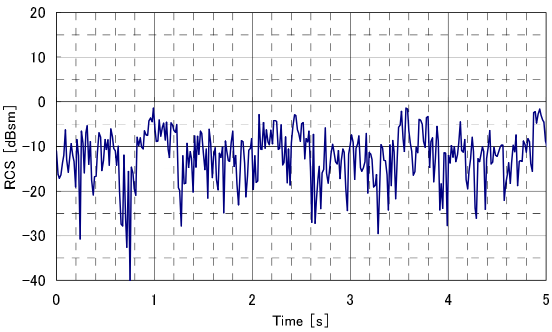


Fig22. Walking state (6-year old child).

Requirements and example dummies compatible with camera detection Since body types and shapes differ due to body size and posture, pedestrian detection by camera uses statistical pattern recognition [13]. Recent research has focused on methods using image features which express the spatial distribution of edges on the image, such as histograms of oriented gradients. Applied methods of these histograms have also been proposed [14-15]. Pedestrian detection also uses edges on images as features, but defining the edges of which part of the body differs to each system. Since the movement of the arms and legs is an important aspect of a dummy simulating a pedestrian crossing a road, the following requirements were identified to develop dummies compatible with camera detection.

(1) Simulation of a realistic human shape (dimensions)

(2) Simulation of arm and leg movement

To satisfy these two requirements, the dummies were developed as follows.

- Reproduce an AM50 physique and walking motion (arm and leg dimensions, and the like)
- Provide the mechanism above the pedestrian dummy (to reduce the effect of the mechanism on the reflection intensity as described above to simulate arm and leg movement.

SAE J2782 (Performance Specifications for a Midsize Male Pedestrian Research Dummy) was referenced to determine the dimensions of the AM50 dummy. The dimensions of the 6-year old child dummy were also determined based on physical data. The walking motion was set to correspond to the stride length defined in pedestrian data. Although walking has been studied in various research, the results differ in accordance with age and body shape. This research used the stride length results obtained by Yamazaki et al. [16]. From these results, the dummy height was set to 175 cm or more, the walking speed was set to 4 km/h, and the average stride length was set to 70 cm.

Figure 14 shows several frames from the walking motion of the AM50 pedestrian dummy that adopted these requirements.

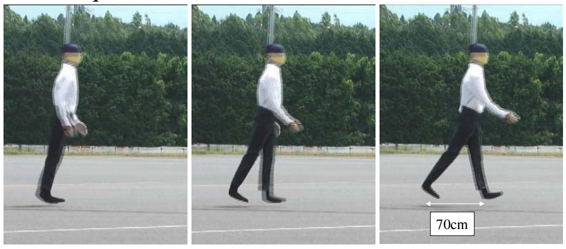


Fig.14 walking motion of pedestrian dummy

Development of Test Apparatus for Evaluation

Based on the details described above, the following requirements were identified for the test apparatus to be attached to the pedestrian dummies.

- Compatibility of a child's walking speed of up to 9 km/h and a maximum lateral appearance position of 6 meters
- No interference with detection of the pedestrian dummies by millimeter wave radar and cameras

Figure 15 shows the developed test apparatus compatible with these requirements. An aluminum truss frame was created to attach the walking mechanism above the dummy. Considering the millimeter wave reflective characteristics of the truss, the width and height were set to 15 meters and 3.6 meters, respectively. A clear pipe was used to connect the walking mechanism and the pedestrian dummy to minimize the effect on the camera.

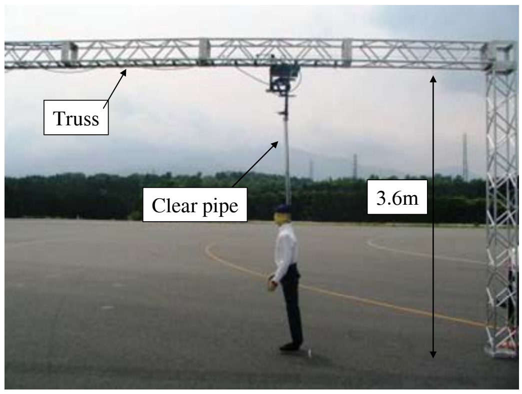


Fig.15 Test apparatus for Pedestrian PCS evaluation

CONCLUSIONS

This paper has described the research results of the method of evaluating PCS for pedestrian detection. The evaluation condition was determined by analyzing the pedestrian accident data. Requirements of the pedestrian detection sensor for a test apparatus were identified. Finally, the test apparatus was developed. The results of the research can be summarized as follows.

(1) Accident scenario of a vehicle going straight ahead while a pedestrian crosses the road account for approximately 60% of all pedestrian fatalities in Japan. Furthermore, a large proportion of accidents involve either elderly pedestrians or children. Consequently, the research focused on accident scenarios involving elderly pedestrians and children crossing a road.

(2) The evaluation conditions of accidents involving elderly pedestrians and children crossing a road were defined based on analysis of pedestrian accident data and near-miss incident data in Japan. Two evaluation conditions were set for accidents involving elderly pedestrians: crossing from the left during daytime and crossing from the right at night. The evaluation conditions for children featured a child emerging suddenly from behind a parked vehicle.

(3) Pedestrian dummies and test apparatus to carry out these evaluations were developed to be compatible with pedestrian detection sensors.

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JOINT MOTION PATTERN OF LIMB MOVING MANNEQUINS FOR ACTIVE SAFETY VEHICLE TESTS

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ABSTRACT

Pre-Collision Systems (PCS) for pedestrian crash avoidance have been equipped on certain high-end passenger vehicles. At present, there is not a common evaluation standard to compare the performances of PCS for pedestrian collision avoidance. The Transportation Active Safety Institute (TASI) at Indiana University-Purdue University-Indianapolis has been studying the establishment of such a standard with support from Toyota Motor Corporation. One task surrounding the development of such a standard is the creation of mannequins that move like real pedestrians. To make a mannequin move like a human being, it should have joints at the hip, knee, shoulder and elbow and be able to plan the joint motion trajectories. The mannequins need to have standing, walking or running gestures during PCS evaluation. A cost-effective source of gaiting information is from papers published in the medical field. These papers reported the joint angle measurements of hundreds of human subjects in all age spans. However, most of the results in these papers were based on gender, age, and heuristic motion speeds. They are not directly useable in mannequin motion planning. This paper aggregates and converts the measured gaiting parameters from many publications into functions of walking/running speed for easier mannequin joint trajectory planning. Specifically, we have successfully extracted and aggregated the measured data of hundreds of subjects reported from many medical gaiting and running publications, and presented them as functions of walking speed. The functions include step size, step frequency, maximum hip flexion, maximum hip extension, maximum knee flexion at stance, maximum knee flexion at swing, and their corresponding occurrence time as the percentage time in a step cycle. The result of this study enables the joint trajectory planning for the mannequin to be used at walking and running speeds.

1. INTRODUCTION

Pre-Collision Systems (PCS) for pedestrian crash avoidance have been equipped on certain high end passenger vehicles. At present, there is not a common evaluation standard to compare the performances of PCS for pedestrians. The Transportation Active Safety Institute (TASI) at Indiana University-Purdue University-Indianapolis has been studying the establishment of such a standard with support from Toyota Motor Corp. One task surrounding the development of such a standard is the creation of mannequins that can represent average pedestrians. Since PCS sensors detect pedestrians partially based on their body sizes and gestures, mannequins not only should be built with heights and body sizes representative of the pedestrian public, but also should be able to show major walking and running gestures. Therefore, TASI is developing limb moving mannequins that look and move like pedestrians. The design of a properly functional mannequin consists of the study of following issues: the frame structure and limb motion mechanism, the size of the mannequin and body parts, the motion ranges and timing of all joints for different walking and running speeds, the mannequin skin development, the mannequin clothing. This paper focuses on the motion ranges and timing of all joints of mannequins for different walking and running speeds.

This paper is organized as follows. Section 2 briefly describes the mannequin motion mechanisms.

Section 3 describes the method of using gait analysis data to obtain the gaiting data for mannequin. The discussion and conclusions are in sections 4 and 5 respectively.

2. BACKGROUND

For a mannequin to move like a human being, it should have the horizontal motion and limb motion. In this study, the horizontal mannequin motion is achieved by hanging the mannequin on a wirelessly controlled trolley running on a gantry crane. The limb motion is achieved by installing motors on mannequin joints. Humans use many joints to control the body motion, such as shoulder, elbow, hip, torso, knee, and ankle. However, due to the constraints in mannequin power consumption, weight, ruggedness, and the significance of each joint towards the walking and running gestures, a motor is installed on each shoulder, hip and knee, and a passive joint is used at each elbow. No joint is installed at the torso and ankle. The mannequin itself can only move limbs but cannot actually walk or run.

During PCS evaluation, scenarios with various speeds of mannequin motion are required. Since pedestrians' gait parameters change with the motion speed and the test scenarios can specify different pedestrian speeds, it is desirable to have the gait parameters described as functions of the pedestrian motion speed in order to control the mannequin motion in different test scenarios. To make a mannequin motion like an average real human from slow walking to fast running, the speed range of 0.5 to 4.3 m/s is required for the mannequin motion. Since the gait information in terms of the motion speed is not readily available, this paper describes a process to obtain the gait information from public domains.

Human gaiting data were searched in the fields of computer animation, human like robotics and biomechanics. Although there are a lot of computer simulations and animations of human beings in video games and movies, the joint motion in most of these programs are based on the artistic drawing but not based on the actual human gaiting data. There is a computer simulation program [1] that provides credible gait simulation. Some data used in this program were contributed from projects sponsored by United States National Institute of Health. The program supports 12 gait animations, each of that is developed based on one of the twelve children age from 7-12 years old. These animations provide all joint data for gait cycles of various walking speeds. Descriptions of the capability of the animation program are in [2, 3]. The theoretical support of this animation program is described in [4, 5]. Other possible walking simulation data and publications can be found in [6-8]. The papers in the walking robot field emphasizes on robot's ability to walk [9]. The gaiting data are generated based on the physics principles and minimum energy usage without the concern of whether the walking robot walks like a human being or not. There are more measured human gaiting data in the field of biomechanics. Some studies collected real measured data from hundreds of human subjects to establish a reference walk pattern for slow, comfortable, and fast walking [11- 14]. This study is to use the data in the biomechanics field to find the joint motion trajectory of average pedestrian in United States with respect to motion speed. The result is divided into four parts: adult walking, adult running, children walking, and children running.

3. PEDESTRIAN MANNEQUIN MOTION PATTERN

3.1 Adult Walking

Two comparable gait measurement studies were conducted in US [10] and Sweden [11, 12] respectively. The gaiting parameters of 260 subjects were measured in US and that of 233 subjects were measured in Sweden. The ages of subjects were from 10 to 79 years old. This amount data is desirable since it can represent the gaiting data for average pedestrians. However, all data in these two studies are grouped based on subjects' ages and three subject interpreted speeds in terms of slow, comfortable and fast. Since PCS detects pedestrians based on their sizes and gestures but not based on ages, the data useful for PCS evaluation should be rearranged to remove the age information and to relate to motion speed information. Fortunately, this data rearrangement is feasible since all subjects described in these papers were required to walk in slow, comfortable and fast speeds interpreted by each subject. Since the interpretation of slow, normal, and fast are different among different subjects, the gait data collected in these two studies covers the spectrum of walking speed in the range from 0.6 m/s to 2.4 m/s. Step sizes and step frequency data in these papers are rearranged and plotted in terms of motion speed (see Figure 1). Each point in Figure 1 represents the data of one age group at one walking condition in one paper. It is well known that the product of step size and the step frequency is the motion speed. Therefore, the product of step size and the step frequency of the same subject group in terms of motions speed is plotted in order to check the quality of the data (see Figure 2). The linear equation generated by curve fitting shows that this plot is a straight line with slop 1.06 which demonstrated that data is accurate. Quadratic functions of the step size and step frequency in respect to the motion speed (see Figure 2) are generated using best fit functions.

Since the height of our adult mannequin is selected as 168 cm which is close to the average height, 169cm, of US adults (including all ages), we assume that the average height of about 520 subjects shown in [10, 11] is close to the average pedestrian of 169 cm tall. Therefore, based on the step size – motion speed equation and step frequency-motion speed equation, the step size and step frequency of the adult mannequin at different walking speeds can be calculated. Additional measured gaiting data of more than 250 human subjects can be found in [13, 15, and 16]. These gating measurement data can be added to the plot in Figure 2 to generate more statistically accurate gating functions.

After obtaining the step size and step frequency of mannequin gaiting, the next step is to find the corresponding joint angles in each gait cycle. The first question is that how many joint angles in each gait cycle are needed. In theory, the more control points used in a cycle, the more realistic motion can be generated. However, the challenge is to be able to find data for all angles in a gait cycle.

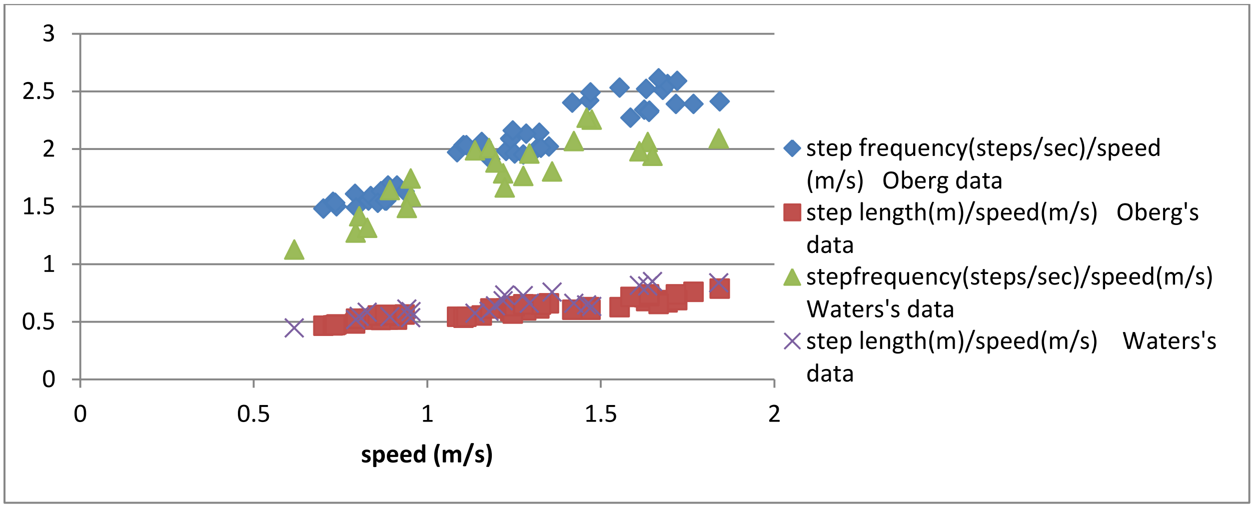

Figure 1. Compare step sizes and cadences in two different studies.

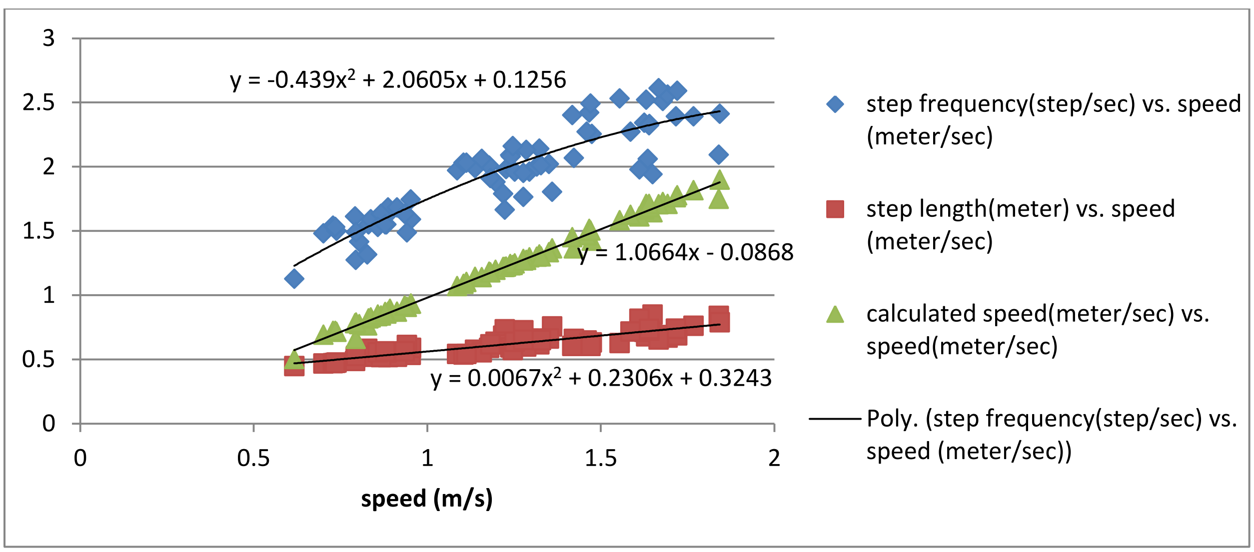

Figure 2. Functions of step size (m) and step frequency (steps/sec) in vertical axes respect to walking speed (m/s) in horizontal axis.

By analyzing the gait cycle, it is decided to use the joint angles where the joint changes the motion directions. Therefore, the joint angles of interest include two extrema angles for the hip motion, two extrema angles for the shoulder motion, and four angles for the knee motion in each gait cycle. Figure 3 shows the four angles of the knee joints at which the knee angular velocity changes the direction.

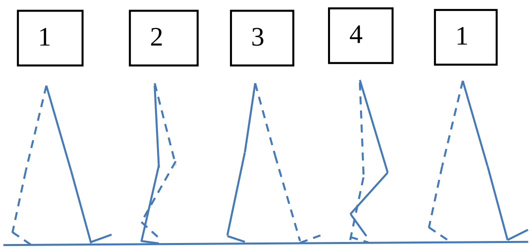

Figure 3. The hip and knee joint angles essential for mannequin gaiting control. For legs shown in solid lines, 1= heel contact, 2= mid-stance, 3= hell-off, 4= mid swing.

The angular velocity of the hip changes the direction only at heel contact location and the heel off location. The angular velocity of the knee changes the direction at all four locations. The extrema hip joint angles are at the maximum flexion and the maximum extension (solid leg in 1 and 3 of Figure 3 respectively). The interested knee joint angles are at heel contact, mid stance, heel off, and mid swing gestures 1 to 4 in Figure 3, respectively). It is assumed that knee angles at both heel contact and heel off positions relative to the thigh are zero in walking. Knee angles at mid stance and mid swing are the maximum flexion where joint motion direction changes. Most gait measurement data includes hip flexion/extension and knee flexion.

Once the extrema joint angles at different walking speed are known, the next question is when do joints reach the extrema angles. Many papers presented the timing of joint angles as the percentages of a gait cycle (%cycle). Figure 4 is a maximum hip flexion figure copied from [17]. Stars are added on the top of the curve showing the maximum hip flexion and on the bottom of the curve showing maximum hip extension with respect to the corresponding %gait cycle. Figure 5 is a modification of another figure in [17] that demonstrates the left knee and right knee angles of interest (marked by stars) corresponding to %gait cycle. The 0% of the right knee is aligned with 50% of the left knee in a gait cycle. Since the % gait cycle of each star point changes as walking speed changes, the next step is to find how the %gait cycles of the star points change as motion speed changes.

Although [12] provided a linear approximation of the knee and hip extrema angles with respect to motion speed (copied to the lower three cells of the middle column of Table 1, the timing of reaching the angles is not shown in [12]. This information is derived from the data provided in [18]. [18] is a survey paper that thoroughly summarized 83 gating publications. [18] also showed the gait timing of the extrema joint angles in terms of %cycles with four different motion speeds (walk (1.2 m/s), run (3.2 m/s), sprint (3.9 m/s), elite sprint (9 m/s)). By curve fitting these %cycles values of each extrema joint angle at 4 different speeds, we obtained the time corresponding each extrema angle with respect to motion speed (see right column of Table 1).

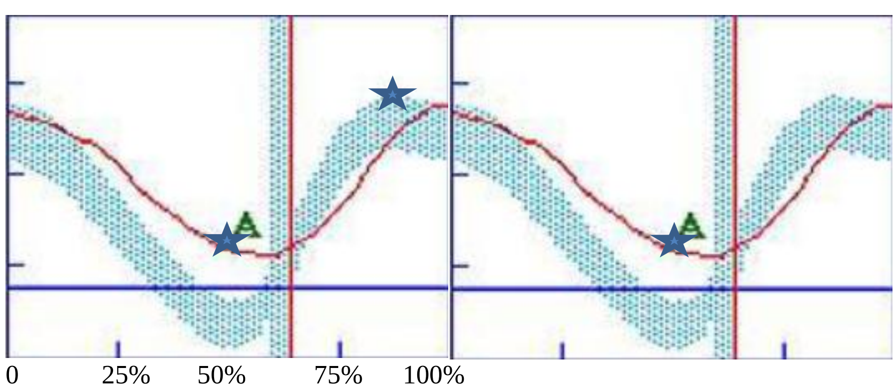

Figure 4. Hip angles with respect of the % of a gait cycle.

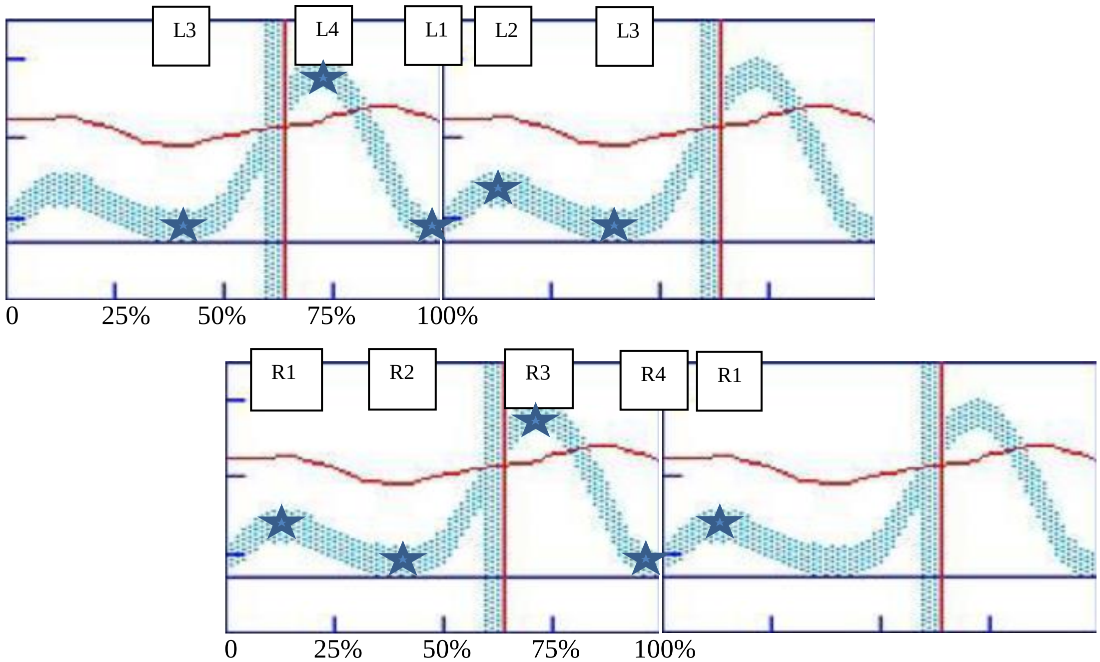

Figure 5. Knee angles with respect of the % of a gait cycle. L1 to L5 are the joint angles and time of consecutive left knee joints. R1 to R5 are the joint angles and time of consecutive right knee joints.

Table 1 is the summary of the gait parameter calculation for adult mannequin

	Equation(related to speed X in cm/sec)	Extreme at cycle percentage(related to speed X in cm/sec)
Step Size (m)	$0.0067*X^2 + 0.2306*X + 0.3243$	
Step Frequency (m/s)	$-0.439*X^2 + 2.0605*X + 0.1256$	
Hip Flexion/ Extension (degrees)	Flexion – Extension : 27.8+016*X	Flexion: $0.5298*X^2 - 8.3022*X + 103.87$ Extension: $0.3272*X^2 - 5.6556*X + 57.385$
Knee Stance (degrees)	Flexion – Extension: 1.25+0.135*X	Flexion : $0.2116*X^2 - 2.9312*X + 43.213$ Extension : $-1.0714*X^2 + 5.4643*X + 5.9857$
Knee Swing (degrees)	Flexion – Extension: 56.7+0.068*X	Flexion : $-0.0994*X^3 + 1.4069*X^2 - 7.6479*X + 79.323$ Extension : $0.2384*X^2 - 2.5343*X + 100.53$

3.2 Adult Running

[18] presented the functions of step length, step frequency, hip angle and knee angle with respect to one specific speed of walking, one specific speed running, and one specific speed sprinting, respectively. The data in [18] also presented joint extrema in these 4 different speeds in respect of percentage of a motion cycle. Here we rearrange the data by curve fitting each extreme joint angle at these 4 given speeds and mapping the joint angles and the %cycle time respect to the motion speed. Therefore we can derive the joint angles and %cycle time for a specific adult running speed using these functions. Figure 6 shows step length, step frequency (cadence), stride time (2 steps) and non-support (foot off-ground time) functions in terms of the running speed. Figure 7 shows four knee flexion/extension extrema angles with respect to the running speed. Figure 8 shows %cycles at which the extrema knee flexion/extension occur with respect to the running speed. Figure 9 shows two thigh extrema position in terms of running speed. Figure 10 is the %cycle values at which two thigh extrema occur in a running cycle. Table 2 summarizes the extrema joint angles and their corresponding %cycles.

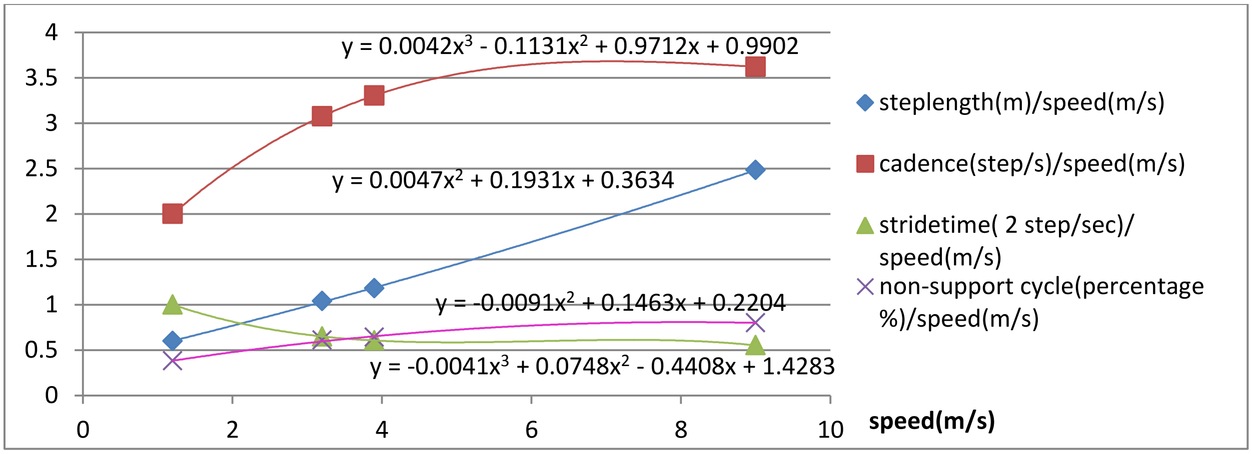

Figure 6. Adult running step length (m) and step frequency (steps /s) vs. running speed (m/s).

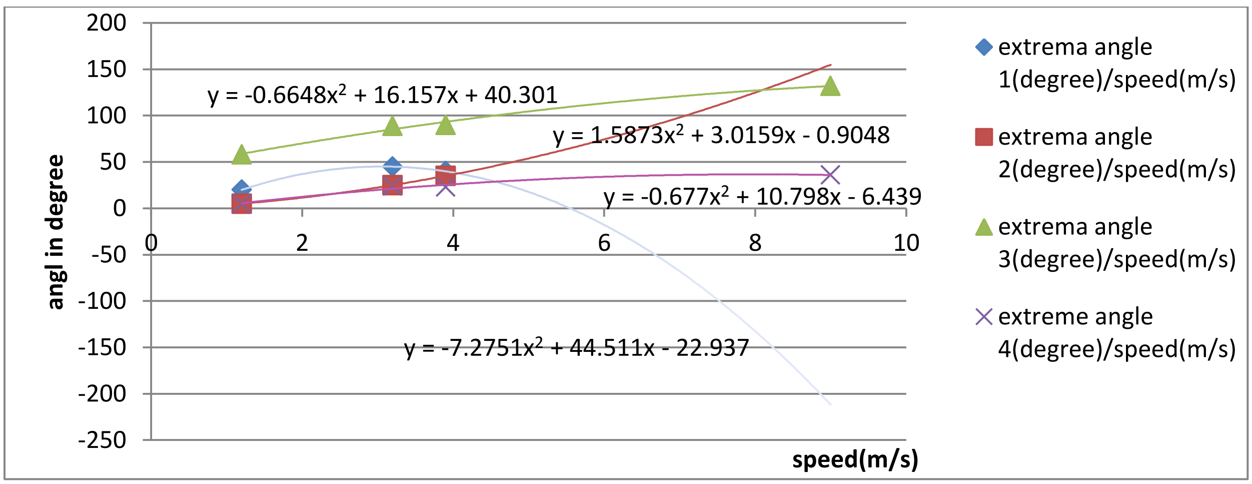

Figure 7. Adult knee angle vs. speed.

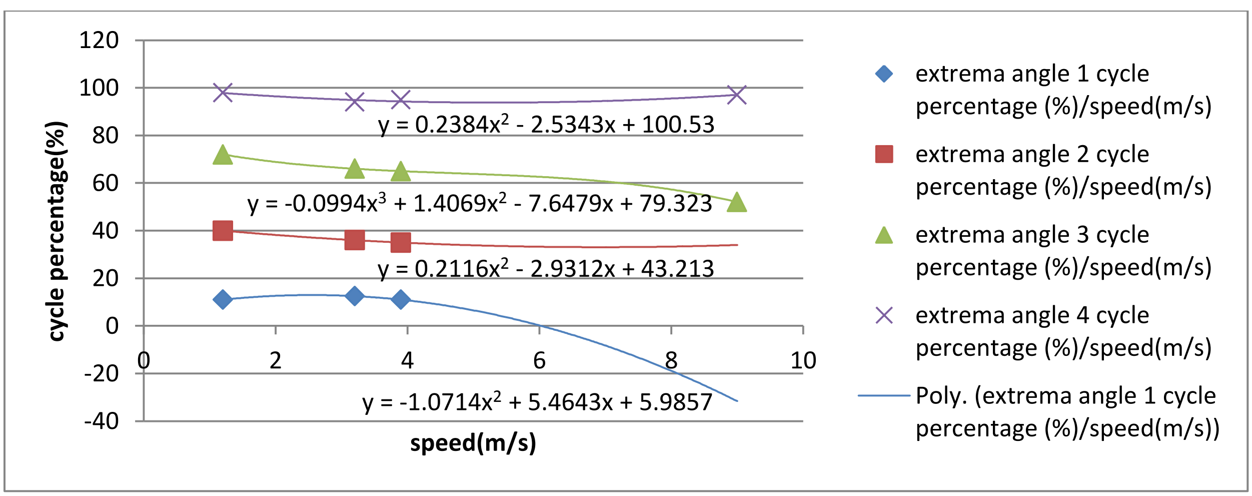

Figure 8. Adult knee %cycle vs. running speed.

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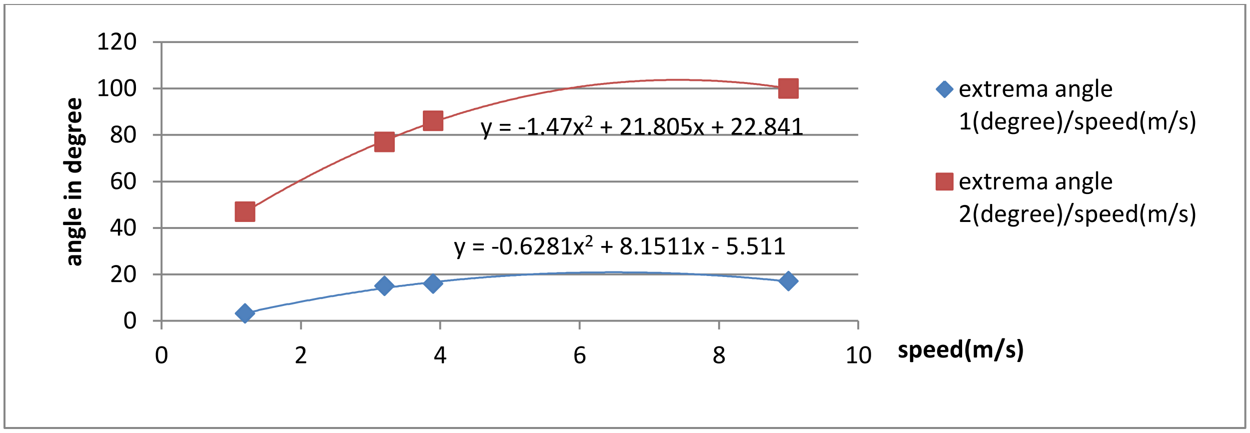

Figure 9. Adult thigh angle vs. running speed.

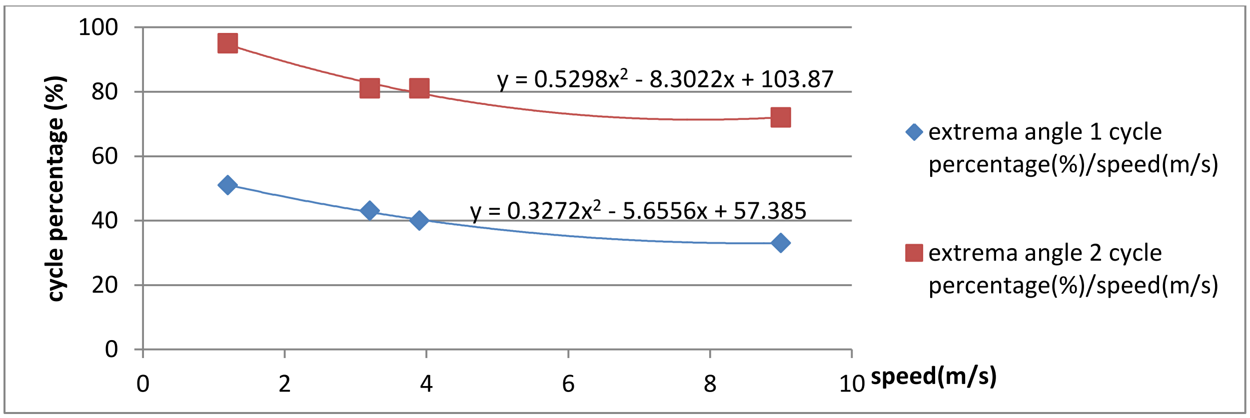

Figure 10. Adult thigh %cycle vs. running speed.

Table 2. Mannequin motion control parameters for adult running

	Equation (related to speed X in m/sec)	**Extreme %cycle (related to speed X in m/sec)**
Step Size (m)	$0.0047*X^2 + 0.1931*X + 0.3634$	
Step Frequency (steps/s)	$0.0042*X^3 - 0.1131*X^2 + 0.9712*X + 0.9902$	
Thigh position (femur relative to vertical, degrees)	Flexion: $-1.47*X^2 + 21.805*X + 22.841$ Extension : $-0.6281*X^2 + 8.1511*X - 5.511$	Flexion : $0.5298*X^2 - 8.3022*X + 103.87$ Extension : $0.3272*X^2 - 5.6556*X + 57.385$
Knee Stance (degrees)	Flexion : $-7.2751*X^2 + 44.511*X - 22.937$ Extension : $1.5873*X^2 + 3.0159*X - 0.9048$	Flexion : $0.2116*X^2 - 2.9312*X + 43.213$ Extension :$-1.0714*X^2 + 5.4643*X + 5.9857$
Knee Swing (degrees)	Flexion : $-0.6648*X^2 + 16.157*X + 40.301$ Extension: $-0.677*X^2 + 10.798*X - 6.439$	Flexion : $-0.0994*X^3 + 1.4069*X^2 - 7.6479*X + 79.323$ Extension : $0.2384*X^2 - 2.5343*X + 100.53$

3.3. Children Walking

The same approach was tried to find the joint angles and occurring timing for children as that for adult walking. However, there is very limited number of publications related to children gaiting. [14] provided the measured walking step lengths and cadences of 20 Brazilian children from 3 to 6 years old, which is plotted with respect to walking speed in Figure 11. The functions of step length and step frequency with respect to walking speed are generated using least mean square curve fitting. No joint angle information measured in the study reported in [14]. [19] provided the hip and knee extrema angles of 28 children of 5-6 years old at a specific walking speed and also provided the timing of the joint angle changes. [20] provided the measured gait parameters of 16 children during their growth from 7 to 12 years for 5 consecutive years, and provided detailed knee maximum swing flexion, stance flexion, and hip flexion/extension with respect to %gait cycles. [1] provides credible gait simulation because the data used in the program is contributed from projects sponsored by National Institute of Health. The program supports 12 gait animations each of which is developed based on one of the twelve children age from 7-12 years old. These animations provide all joint data for gait cycles of four different walking speeds. In summary, since the height and the leg length of children vary significantly from 5 to 12 years old, the available data is not sufficient to draw conclusion on how a representative six years old child (average 108 cm tall) walks. However, the available data in above referenced publication allow us to find the measured gaiting data of at least one child of specific height for a given walking speed.

3.4 Children running

[14] also provided the measured running step lengths and cadences of 20 Brazil children from 3 to 6 years old which is plotted with respect to running speed in Figure 12. The functions of step length and step frequency with respect to running speed are generated using least mean square curve fitting. However, joint angles and timing were not measured in the study reported in [14]. More data search need to be conducted to find the children running information.

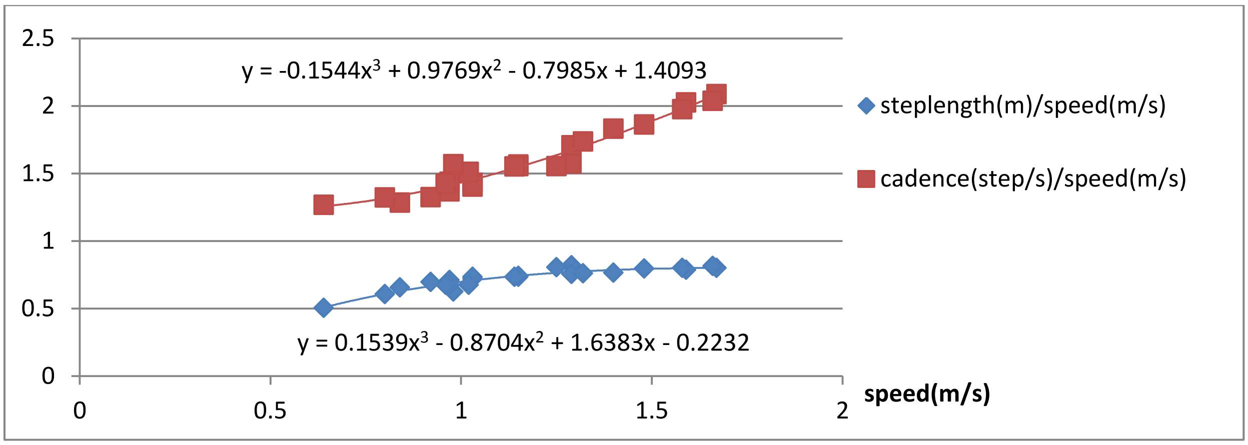

Figure 11. The relationship of cadence and step length with respect to walking speed for 20 Brazil children from 3 to 6 years old (the unit of the speed is m/s and the unit of the step length is meter).

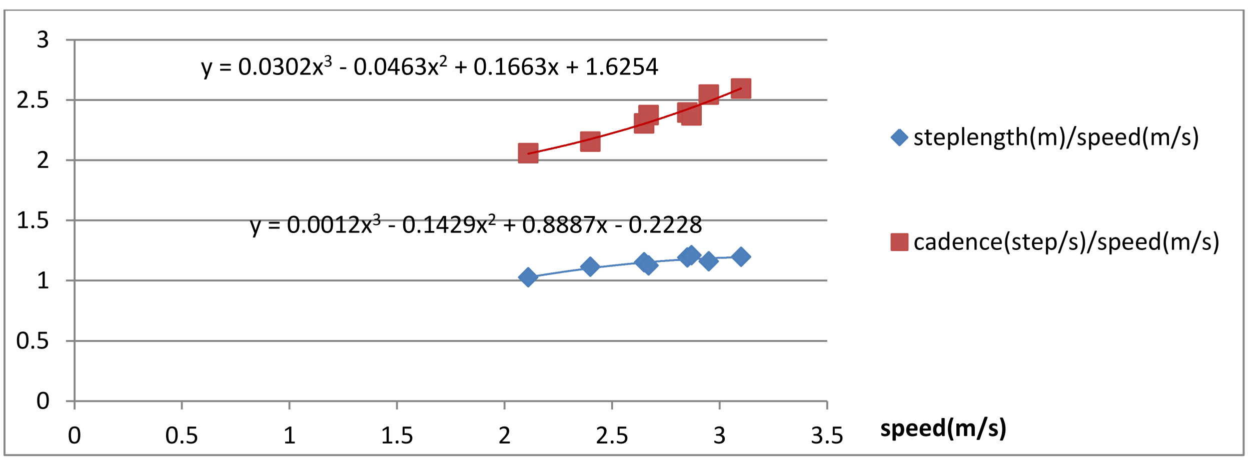

Figure 12. The relationship of cadence and step length with respect to running speed for 20 Brazil children from 3 to 6 years old (the unit of the speed is m/s and the unit of the step length is meter).

4. DICUSSION

We did not find the biomechanics publications containing the measured shoulder and elbow joints data. Since the arm motion is to counterbalance the body rotation caused by leg motion, we will use the same hip joint trajectory data (frequency, angle and timing) on the opposite shoulder.

5. CONCLUSIONS

We extracted and aggregated the measured data of hundreds of adult subjects reported from many medical gaiting and running publications, and presented them as functions of walking speed. The functions include step size, step frequency, maximum hip flexion, maximum hip extension, maximum knee flexion at stance, maximum knee flexion at swing, and their corresponding occurrence time as the percentage time in a step cycle. There is very limited data for obtaining the representative data for children but there is gating data for child mannequin to mimic the gate motion of individual child at specific walking speed. The result of this study enables the joint trajectory planning for the adult mannequin at walking and running speeds.

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