ANTI LOCK BRAKING AND VEHICLE STABILITY CONTROL FOR MOTORCYCLES – WHY OR WHY NOT?

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ABSTRACT

In the last years there has been a decline in accident figures in Germany especially for four wheeled vehicles. At the same time, accident figures for motorcycles remained nearly constant. About 17 % of road traffic fatalities in the year 2006 were motorcyclists. 33 % of these riders were killed in single vehicle crashes. This leads to the conclusion that improving driving dynamics and driving stability of powered two wheelers would yield considerable safety gains. However, the well-known measures for cars and trucks with their proven effectiveness cannot be transferred easily to motorcycles.
Therefore studies were carried out to examine the safety potential of Anti Lock Braking Systems (ABS) and Vehicle Stability Control (VSC) for motorcycles by means of accident analysis, driving tests and economical as well as technical assessment of the systems.
With regard to ABS, test persons were assigned braking tasks (straight and in-curve) with five different brake systems with and without ABS. Stopping distances as well as stress and strain on the riders were measured for 9 test riders who completed 105 braking manoeuvres each.
Knowing the ability of ABS to avoid falls during braking in advance of a crash and taking into account the system costs, a cost benefit analysis for ABS for motorcycles was carried out for different market penetration of ABS, i.e. equipment rates, and different time horizons.
The potential of VSC for motorcycles was estimated in two steps. First the kinds of accidents that could be prevented by such a system at all have been analysed. For these accident configurations, simulations and driving tests were then performed to determine if a VSC was able to detect the critical driving situation and if it was technically possible to implement an actuator which would help to stabilise the critical situation.

INTRODUCTION

Compared with cars, the most critical vehicle factor for a motorcycle is the fact that it uses only one-track instead of two. So tilting of the motorcycle has to be avoided by steering and by the stabilizing forces of the wheels. This leads also to the seriousness of wheel locking while braking when the gyro forces and, even more important, the side forces at the front wheel vanish.
ABS therefore is one of the most promising devices to improve the safety of powered two wheelers. Besides ABS one can imagine other systems designed to stabilise driving dynamics of a motorcycle since they are well known for four wheeled vehicles.
BASt (Bundesanstalt für Straßenwesen), the Federal Highway Research Institute of Germany, therefore initiated several research projects which were carried out by Darmstadt University of Technology and University of Cologne.
The first task of the studies was to formulate requirements applicable to brake systems with which the motorcyclist can reproducibly achieve safe braking operations with short stopping distances. For that purpose ABS and combined braking systems were examined. Since ABS was identified to avoid fall events during braking manoeuvres and to reduce stopping distances also while braking in bends, a cost-benefit analysis was carried out in a second stage to clarify whether the economic benefit of ABS for motorcycles is greater than the consumed resources. In a third study the possibility to detect critical driving situations of motorcycles objectively which would be the basis

for every application of a driving stability system for motorcycles was examined. By means of studying accident figures as well as the technical possibilities for the implementation of VSC on motorcycles, possible safety gains were determined.

ANTI LOCK BRAKING SYSTEMS

Stress and Strain on motorcycle riders while braking

The technical benefit of anti-lock brake systems for the rider's safety has been shown in many research studies concerning achieved decelerations or braking distances when braking straight or in curve, and is undeniable [1, 2]. Furthermore, research was able to show that motorcycles equipped with ABS would decrease the number of accidents and the number of severely injured riders and fatalities in real-life scenarios [3].
In this research project, mental strain depending on the kind of brake system was tested. Deducted from the fact that test persons on a closed test track achieve higher decelerations with ABS and so suffer from higher acceleration forces, the working hypothesis was to test if this higher physical stress leads to higher physical strain.
Mentally the stress in real life conditions is obviously higher than in test conditions on a closed test track, but only defined test track conditions make the mental stress at different times comparable. Measuring the physical stress and strain at constant mental stress then makes it possible to deduct indications for mental strain.

Test Layout

On Griesheim Airfield, a closed test track with unevenness comparable to a German Highway [5] and a relatively high friction coefficient [4], three test scenarios have been built up:

- Full braking from 60 km/h straight,
- Full braking from 90 km/h straight,
- Full braking from 50 km/h in-curve, with 50 m radius (i.e. < 20° rolling angle)

All three took place on a wet road surface with one test motorcycle, a BMW R1150RT, see fig. 1, equipped with alternatively choosable the original combined ABS ("BMW i-ABS" first Generation, also known as FTE CoraBB) or the BMW R1100RT standard brake system with ABS ("BMW ABS II"), both disengageable, and a removable rear brake lever. With each of these 5 brake systems – standard brake without ABS, standard brake with ABS, combined brake without ABS, combined brake with ABS, combined brake with ABS and only the hand lever – 9 test persons had to absolve the test round 7 times. The sequence of brake systems had been permuted in three permutations that way, so neither a brake system had been used on the same place nor was followed by or preceding the same system a second time. For a better understanding, table 1 shows the three permutations. Each rider was allocated a specific permutation.

Table 1.
Test layout; permutation of brake systems

Permutation A	Permutation B	Permutation C
standard brake	combined brake with ABS	combined brake
combined brake	standard brake with ABS	combined brake with ABS, only hand lever
standard brake with ABS	standard brake	combined brake with ABS
combined brake with ABS	combined brake with ABS, only hand lever	standard brake
combined brake with ABS, only hand lever	combined brake	standard brake with ABS

Furthermore, the motorcycle was equipped with a pair of outriggers that catch the motorcycle at around 35° roll angle, so rider and motorcycle don't painfully touch the ground in case of a locked front wheel, see figure 1.
Beyond motorcycle test data such as wheel speeds, front and rear suspension strokes, brake and clutch lever travel, steering angle, and yaw and roll rate, human data such as the tonicities of musculus flexor digitorum (left hand) and musculus trapezius pars descendens (right side) have been recorded as well as the heart frequency. Between the tests,

Figure 1. Test motorcycle BMW R1150RT; during braking tests with integrated and hidden measurement instrumentation and outriggers to limit damage in case of a fall

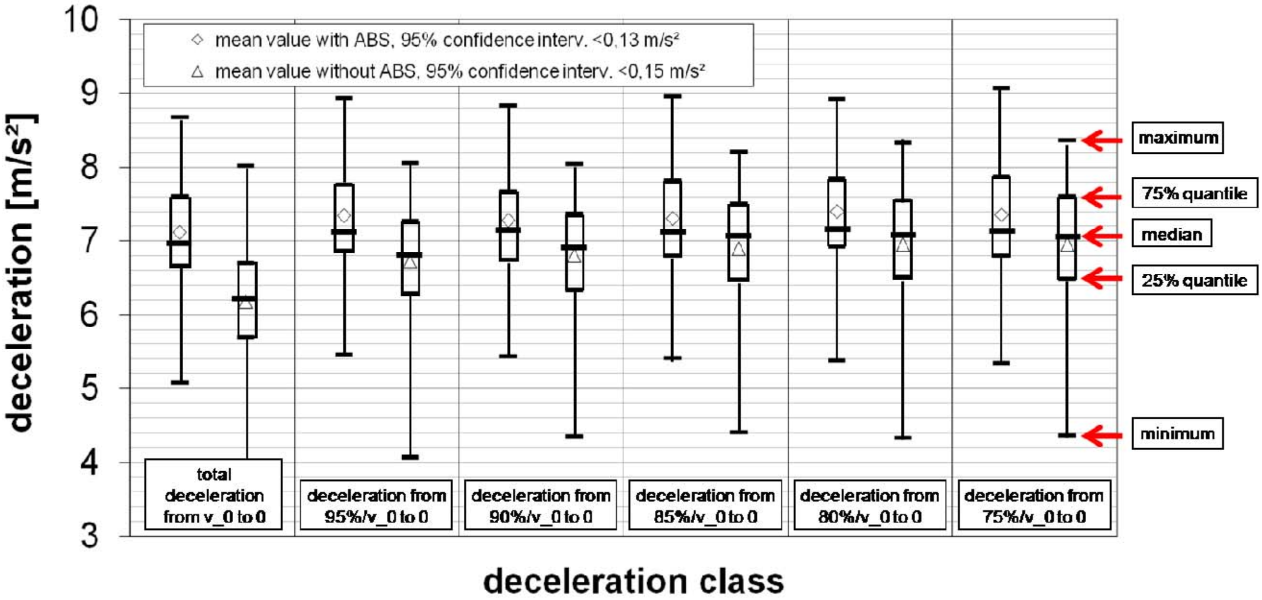

Figure 2. 90km/h straight braking with and without ABS – characteristic data)

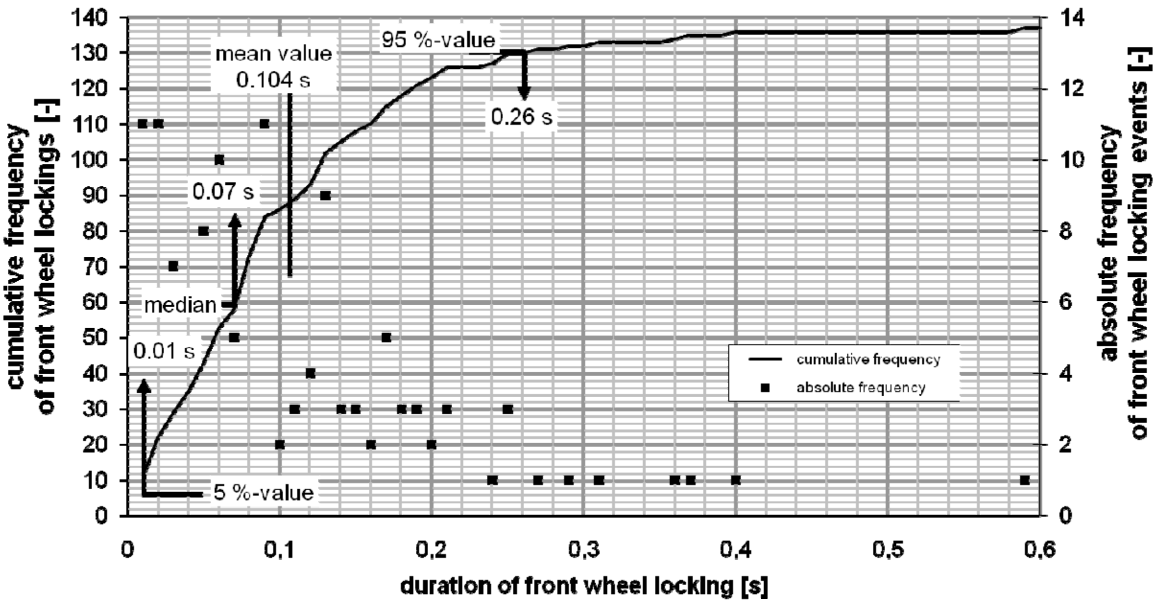

Figure 3. Absolute and cumulative frequency of front wheel locking events and front wheel locking times (100% wheel slip) without fall relevance during tests to minimize braking distance

when changing the brake system, a short mental state test [6] was carried out.
9 male test persons in the age bracket 21 years to 33 years absolved the braking tests; all of them are experienced riders with a riding experience between 18,000 km and 200,000 km.

Test results

Regarding braking distances, this research project confirms investigations which show that riders achieve shorter braking distances with ABS than without, even on a closed test track.

Figure 2 shows, where riders lose time and travel; at the very beginning of a braking manoeuvre the rider has to experience first the pressure point and then optimize the brake pressure for maximum deceleration. To complicate this manual tire slip control, the approach towards the optimum can only happen from the safe side, and the first moments of a braking manoeuvre are highly non-linear regarding wheel loads and provided tire forces [7]. Front wheel lock events have to be extremely short to be absolved without fall, see figure 3, though there is evidence for a fall after less than 0.5 s front wheel lock (figure 4).

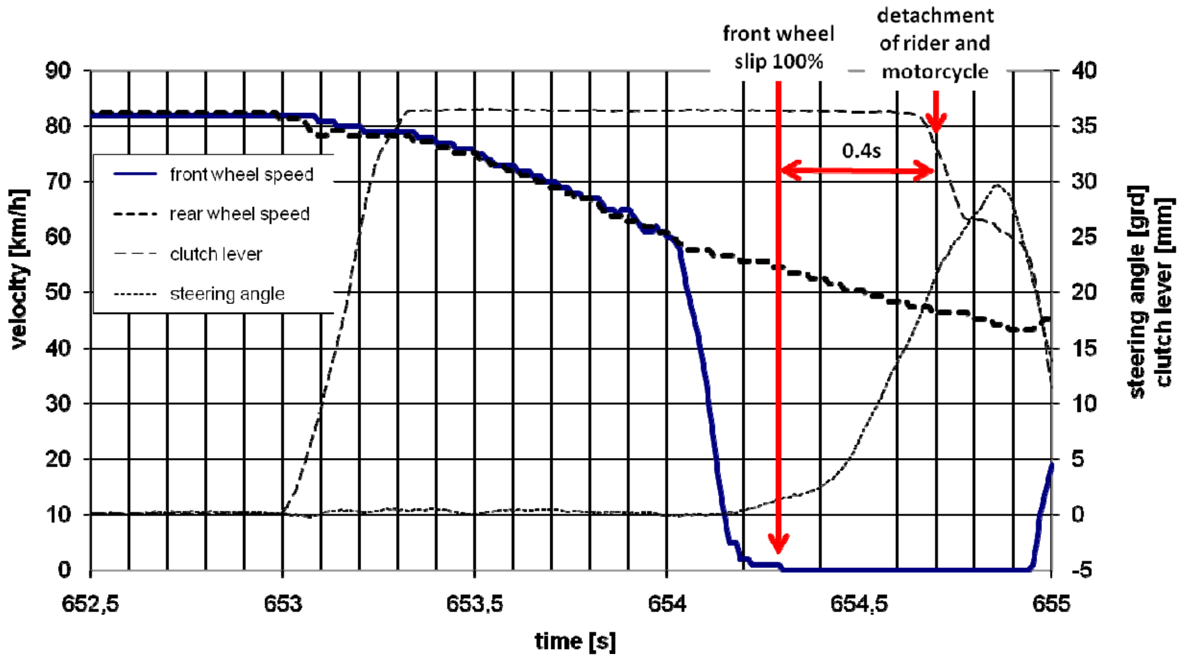

Figure 4. Fall 0.4 s after beginning front wheel locking

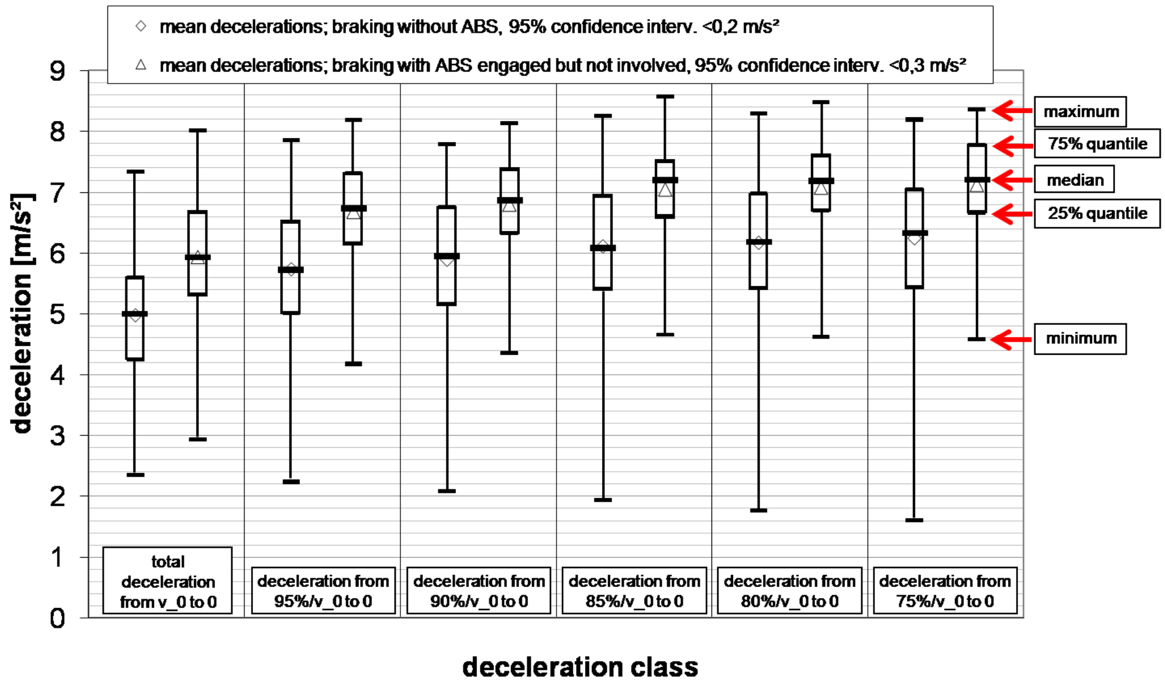

Figure 5. Time based deceleration without ABS and with ABS, but without intervening ABS control, 50km/h in-curve braking

What figure 2 shows for the straight braking at 90km/h is also valid in a weaker form for straight braking at 60km/h and – much stronger – for in-curve braking at 50km/h.
For the more challenging in-curve braking the higher achieved decelerations do not go along with using ABS; most of the braking manoeuvres happen without ABS intervention, but the decelerations achieved with engaged but not intervening ABS are significantly higher than those with disengaged ABS, see figure 5.

So just the presence of ABS makes riders achieve higher decelerations, especially during more challenging braking situations.
There is low significance between brake performance and rider experience. Only the very experienced riders (70,000 km+ riding experience), who also have experience with combined braking systems and ABS, achieve significantly higher decelerations with all kinds of brake systems; the most experienced rider (200,000 km riding experience) delivers the best brake performance, see figure 6.

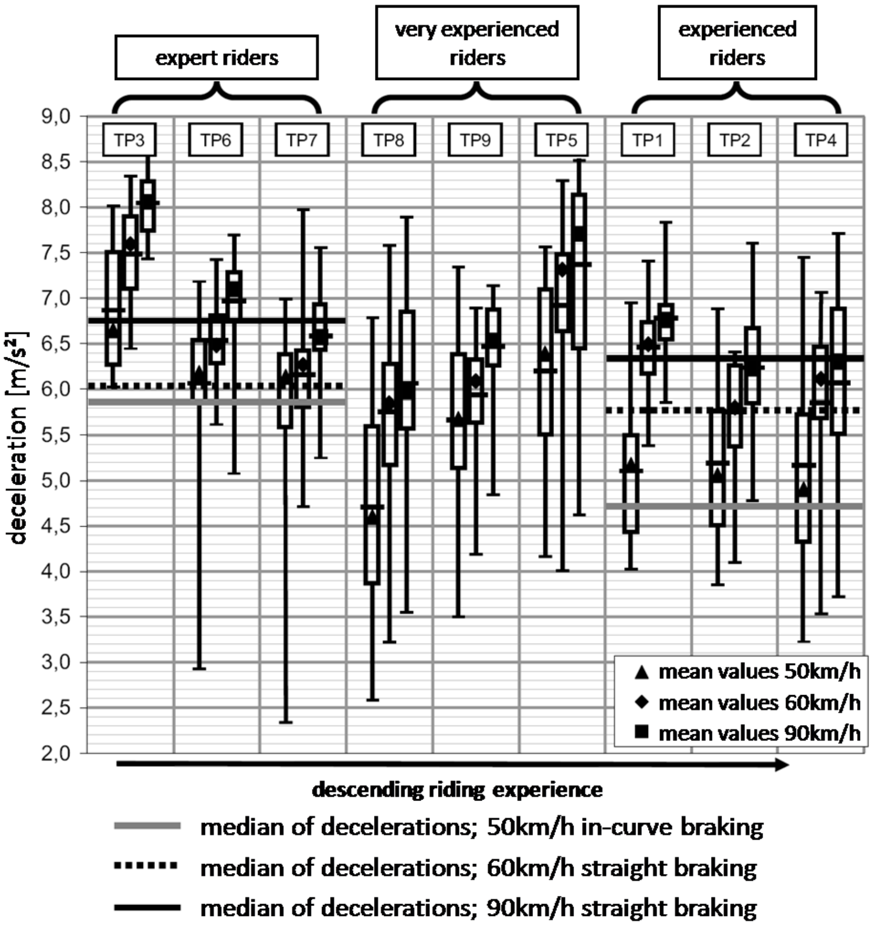

Figure 6. Decelerations of test persons, graded in descending riding experience

His in-curve braking performance is higher than the 90km/h straight braking performances of those test persons with less riding experience!
Those shorter braking distances result from higher decelerations. Higher decelerations mean higher inertia forces on the rider, and this means higher physical stress on the rider. Mental stress objectively is unchanged except for the fact that one brake system differs from another. So as a first conclusion this objectively higher physical stress should be measureable as higher physical strain, if the choice of the brake system has no influence on mental stress and so mental strain remains unchanged.
The majority of the test persons do not show any significant change in the heart rate depending on the brake system, but the other test persons show a significantly higher heart rate when doing the tests without ABS compared to the tests with ABS. Absolute heart rates can exceed 170bpm when absolving tests without ABS compared to 120bpm with ABS. Furthermore, while braking without ABS, all of the test persons show significantly higher tonicities of both musculae measuring points than during the test cycles with ABS.
There is no significance regarding combined and standard brake systems. Giving the rider just the hand lever with the combined brake system with ABS leads to no disadvantages regarding braking performance. Especially for in-curve braking, braking with the combined brake system with ABS is slightly advantageous with just the hand lever vs. both levers.
It could be shown, that the least experienced riders profit more from having ABS than the most experienced riders with regard to braking performance and especially mental strain, s. [8].

Conclusions

Anti-lock brake systems not only prevent rider and motorcycle from harm and damage by increasing active safety, but also reduce significantly mental strain while riding and braking. In case of a critical riding situation, this higher remaining mental reserve would help the rider to develop and wishfully realize alternative emergency strategies that additionally could help the rider to prevent a crash. These advantages are not expected to be neutralized by taking higher risks, as real world investigations show [9].

Outlook

Anti-lock braking systems in motorcycles today give a lot of benefit to the customer. As the press is more and more comparing ABS of different makes and its collateral effects such as brake feeling with and without intervening ABS control, ABS in-curve performance, friction step performance and last, but first in mind and benchmark, performance and feeling on uneven road surface, this will have more and more impact on ABS development. Especially uneven road behaviour and performance could be easily improved and with many positive side effects by an electronic suspension control that provides both high forces at low damping speeds for pitch control and low basic hydraulic forces for good response behaviour, like e.g. electrorheologic damping units can [10, 11].
Regarding the test results and the increasing technical safety level of motorcycles, there is no reason why regulations force motorcycle manufacturers to design two brake levers. When equipped with a combined ABS, the equipment with only the hand lever would not lead to disadvantages regarding brake performance in any way [8].

COST-BENEFIT ANALYSIS OF ABS FOR MOTORCYCLES

As the braking test showed a great safety potential is expected for ABS for motorcycles. The system is thus considered from the economic view. A cost-benefit analysis shall clarify whether the economic benefit of ABS for motorcycles is greater than the consumed resources. A break-even analysis completes the analyses. In this analysis ABS is considered from the end user view.
The considered time horizon for these analyses are the years 2015 and 2020, the area under consideration is Germany. For each of these years the accident data is forecast. At this, it is assumed that the frequency of having an accident per million registered motorcycles decreases based on the present trend. Thus, riding motorcycles gets safer. Hence, the accident data in the years 2015 and 2020 is lower than the accident data today.

Cost-benefit analysis process

In general the CBA consists of a four step process. These four basic steps can be characterized as follows:
In the first step of the procedure the relevant alternatives that will be compared within the analysis have to be defined. For the CBA two cases are introduced:

- The "with-case", which means that a road safety technology/measure like ABS will be introduced.
- The "without-case", which assumes that there will be no implementation of the technology/measure to be evaluated.

Within the second step the potential safety impact has to be quantified. Conceptually, the main effect of road safety technologies/measures such as ABS for motorcycles is the reduction of hazardous situations which affects the number and/or the severity of accidents. As a consequence, accident costs can be lowered.
Within the third step of the CBA process, the benefits are calculated in monetary terms by valuing the annual physical effects with standardized cost-unit rates. In addition to the monetarization of the physical benefits, the costs of the technology/measure have to be determined. The costs comprise the costs to be borne for implementation, operation and maintenance.
The result of the economic evaluation is obtained in the fourth step by comparing economic benefits with costs. For this comparison several measures can be calculated. The most common one is the benefit-cost-ratio (BCR) according to which a technology/measure is macro-economically profitable, if the calculated ratio is greater than one.

$$BCR_t = \frac{B_t}{C_t}, \text{ with} \qquad (1)$$

BCR benefit-cost ratio,
t time horizon defined,
B estimated value of benefits for t
and
C estimated value of costs for t.

The value of the ratio indicates whether the implementation of ABS is favourable from a socio-economic point of view. A BCR of more than "1" indicates that benefits exceed the costs. Thus, the introduction of ABS would be beneficial to society. Furthermore, the value of the BCR expresses the absolute profitability of ABS which can be interpreted as the socio-economic return for every monetary unit (e.g. Euro, US-$) invested in the

implementation of ABS. For example, a BCR of “3.5” would show that 3.5 monetary units can be gained for society for every monetary unit provided for the investment evaluated. Setting absolute, monetized values of benefits and costs into relation, the BCR is a reliable indicator of efficient resource allocation.
In the cost-benefit analysis the costs and the benefits have to be determined. While the calculation of the physical benefits of ABS on basis of accident statistics and accident research is rather straightforward, the monetary valuation of accidents – that means the monetary valuation of injuries and human life – is a controversial matter. In this study the cost-of-damage approach is used to assess the value of the resource savings for the benefit categories.
The cost-of-damage approach is state of the art for cost-benefit analyses which are performed for Germany. The cost-of-damage approach is based on the total estimated amount of economic losses caused by any physical impact. Generally, the losses are quantified via the decline of gross product. For instance, the costs of an accident include the vehicle damage, medical and emergency costs and lost productivity of killed or disabled persons.
In general, there are different benefits due to accident savings which have to be assessed. But in the case of ABS for motorcycles only the safety potential is relevant. Due to the facts that a motorcycle is a narrow vehicle and that most avoidable accidents occur on rural roads with less traffic [12, 13], congestion due to the motorcycle accident is not a problem. In addition, the usage of ABS does not influence the traffic flow.

Scenarios

There are two ABS scenarios considered for each year:

- penetration rate for ABS: trend and
- penetration rate for ABS: mandatory for new motorcycles

The penetration rate is differentiated into a trend scenario and a mandatory scenario. Trend scenario means that there are no special incentives to promote ABS on the part of the politics. In opposition to that the mandatory scenario means that ABS is equipped in every new motorcycle from the year 2010 on.

Table 2.
Equipment rates and the motorcycle stock for the years 2015 and 2020 [14]

Year	equipment rate trend	equipment rate mandatory	motorcycles in 1,000
2015	39.7%	47.8%	4,538
2020	56.7%	69.3%	4,939

The equipment rates and the motorcycle stock for the years 2015 and 2020 can be seen in Table .
The system costs depend on the produced volume. The more systems are produced the lower are the system costs. Hence, the system costs of the mandatory scenario will be lower than the ones of the trend scenario. For the year 2015 the system costs are estimated as 120 Euro for the trend scenario and as 115 Euro for the mandatory scenario. For the year 2020 the figures are 105 Euro and 100 Euro respectively. Economies of scale and effects of learning curves are included.
It is considered that ABS influences the total number of accidents, of fatalities, of severe injuries and of slight injuries. Only accidents in which the motorcycle rider falls down before the real accident happens are considered. The fall is usually caused by locked wheels due to inappropriate braking manoeuvers which can be avoided by ABS. Additional effects due to shorter braking distances with ABS are neglected. This is due to the lack of data. Hence, both scenarios are underestimating.
In order to determine the number of avoidable accidents and casualties, the accident base for 2015 and 2020 has to be estimated (Table).

Table 3.
Estimated accident base for 2015 and 2020 [14]

	accidents	fatalities	injuries severe	injuries slight
2015	34,838	777	9,672	23,561
2020	34,487	746	9,058	23,275

Safety potential

Due to the usage of ABS, falls can be avoided. In every fifth single vehicle accident the motorcycle driver falls down [15]. Every fifth motorcycle accident is a single vehicle accident [12], thus, the share of falls in single vehicle accidents based on all accidents is 4 %. The same calculation is done for multi-vehicle accidents. Here, the share of falls is 10 % [16] while the share of multi-vehicle accidents is 80 %. Thus, the share of falls in multi-vehicle accidents based on all accidents is 8 %. Together, the share of falls based on all accidents is 12 %. The potential of ABS is to avoid 20 % of all accidents with falls [16]. Hence, due to ABS the number of accidents can be reduced by 2.4 %.
The avoided fatalities, severe and slight injuries can be differentiated into three groups:

1. ABS avoids the fall of the motorcycle but cannot avoid the crash (motorcyclist),
2. ABS can avoid the accident (motorcyclist) and
3. ABS can avoid the accident (other traffic participant).

The risk of being killed in an accident with previous fall is twice as high as for accidents without fall. ABS can avoid a fall in 85% of all cases and the share of fatalities after a fall is 22.6 % [12, 14] so that the avoidance potential due to the avoided fall is 9.59 %.
For calculating the avoidance potential of fatalities due to the avoided accident, the share of avoidable accidents (single vehicle and multi-vehicle accidents) has to be multiplied with the accordant share of fatalities in the accident category over the share of the accident category. This is done for single and for multi-vehicle accidents. All in all, the avoidance potential of fatalities due to the avoided accident is 2.26 %.
Finally, the potential in avoiding fatalities of other traffic participants has to be determined. 90 % of all fatalities due to an accident with motorcycles are motorcyclists [12].
Thus, per killed motorcyclist comes 0.11 killed other traffic participant. The share of fatalities of multi-vehicle accidents is 71 % [17]. Thus, 0.156 killed other traffic participants comes on one killed motorcyclist in multi-vehicle accidents. This figure has to be multiplied with the share of avoided fatalities in multi-vehicle accidents (1.29 %). This leads to an additional share of avoided other traffic participants due to avoided accidents of 0.2 %.
In total, 12.05 % of all fatalities can be avoided if every motorcycle is equipped with ABS.
The calculation for the avoidance potential of severe and slight injuries is similar to the one for fatalities. The results for accidents, fatalities, severe and slight injuries are displayed in Table .

Table 4.
Avoidance potential for accidents and casualties [14]

avoidance potential for			
accidents	fatalities	severe inj.	slight inj.
2.4%	12.1%	11.7%	-2.1%

In Germany, ABS for motorcycles was introduced in 1988 by BMW [7]. Today the equipment rate of the motorcycle fleet is significant. Thus, ABS avoids already accidents and, linked to this, casualties. Due to this, the accident data is underestimating – if ABS had never been introduced the accident data would be higher. The estimated accident data for 2015 and 2020 are valid for the trend scenario. For both scenarios the accident data has to be determined for the case that ABS is not available. The adjusted accident base (aab) can be determined as follows:

$$aab = \frac{estimated\ accident\ base}{1 - eq.rate * effectiveness} \qquad (2)$$

The difference of the adjusted accident base and the estimated accident base is the avoidance potential of the trend scenario. The avoidance potential of the mandatory scenario is the following product:

$$potential = aab * eq.rate * effectiveness \qquad (3)$$

In
Table the results are displayed.

Table 5.
avoided number of accidents and casualties in 2015 and 2020 for the trend and mandatory scenario [14]

			injuries	
	accidents	fatalities	severe	slight
2015	34,838	777	9,672	23,561
aab	35,173	816	10,143	23,364
potential trend	335	39	471	-197
potential mandatory	403	47	567	-237
2020	34,487	746	9,058	23,275
aab	34,962	801	9,701	22,999
potential trend	475	55	643	-276
potential mandatory	581	67	786	-338

Benefits

Afterwards the avoided fatalities, severe and slight injuries have to be multiplied with the accordant cost-unit rates. For fatalities the cost-unit rate is 1,190,335 Euro, for severe injuries 101,099 Euro and for slight injuries 13,923 Euro [19].
For each year and for each scenario the avoided accident numbers have to be multiplied with the accordant cost-unit rates for the casualty categories fatalities, severe and slight injuries. Afterwards the sum of the three figures is established. The safety benefits are:

- 91.4 million Euro for the year 2015 in the trend scenario,

- 110.1 million Euro for the year 2015 in the mandatory scenario,
- 126.9 million Euro for the year 2020 in the trend scenario and
- 154.9 million Euro for the year 2020 in the mandatory scenario.

Costs

The benefits have to be confronted with the costs. The costs are the product of system costs per year times equipment rate times motorcycle stock. The system costs per year are the product system costs times annuity rate. The annuity rate depends on the economic lifetime of a motorcycle, which is assumed to be 13.2 years [20], and on the discount rate, which is assumed to be 3 % [14]. The annuity rate is determined as follows:

$$AR = \frac{d * (1+d)^n}{(1+d)^n - 1} = \frac{0.03 * 1.03^{13.2}}{1.03^{13.2} - 1} = 0.0929 \quad (4)$$

In 2015, the system costs per year are 11.14 Euro in the trend scenario. The number of equipped motorcycles is 1.8 million motorcycles. Thus, the costs in 2015 trend scenario are 20.1 million Euro. In the mandatory scenario the costs are 23.2 million Euro, in 2020 the costs are 27.3 million Euro respectively 31.8 million Euro.

Benefit-cost results

The benefit-cost ratio is determined by dividing the benefits by the costs. The benefit cost ratio for the year 2015 is 4.6 in the trend scenario and 4.8 in the mandatory scenario. In 2020 the values are 4.7 respectively 4.9.
In comparison to other vehicle safety systems ABS is in the top flight.
Another possibility to assess the economical impact of ABS is the net-benefit. In this approach the costs are subtracted of the benefits. In 2015 the net-benefits are 71 million Euro in the trend scenario and 87 million Euro in the mandatory scenario. The values for 2020 are 100 million Euro and 123 million Euro respectively.

Break-even analysis

Another analysis which is done for ABS for motorcycles is the break-even analysis. In this approach the end user is in the focus. For an average motorcyclist, the market price for ABS is determined for which the costs and the benefits of ABS are the same from a user point-of-view. In this approach the lower risk of the motorcyclist of being killed, severely injured and slightly injured is considered. Afterwards the difference in the risk (with ABS versus without ABS) is multiplied with the accordant cost-unit rates which are now determined by the willingness-to-pay approach [14]. The result is a fair market price of 701 Euro for 2015 respectively 622 Euro for 2020. If the market price is below the fair market price, ABS will be worthwhile for the average user.
Another approach within the break-even analysis is to calculate the critical mileage. Therefore a market price is estimated – 400 Euro in 2015 and 300 Euro in 2020 [14]. Given this market price and the difference of risk for being killed, severely injured and slightly injured, the mileage can be determined for which the costs and benefits for the user are the same. For each mileage which is higher than the critical mileage, ABS is worthwhile. The critical mileage is 2,200 km per year in 2015 and 1,900 km per year in 2020. These mileages are below the mileage on average. ABS is worthwhile for most users.

Result

The benefit-cost analysis shows clearly that ABS for motorcycles is economically reasonable. The full potential of ABS can only be achieved by making ABS mandatory.

SAFETY POTENTIAL OF VSC FOR MOTORCYCLES

In order to assess the potential for future vehicle stability control systems (VSC), the corresponding accident types, vehicle dynamics properties and technical possibilities need to be taken into account: A technical system intended to decrease the rate of fatal accidents should address accident types that have a high risk of being fatal as well as occur often. These accident types are identified by means of an accident analysis.
To gather information on the vehicle behaviour during these accidents, real-world experiments of simulated accidents using a test motorcycle and computer simulation studies with the simulation package VI/Motorcycle are conducted. A mathematical model for the vehicle behaviour is derived from the experiments and computer simulations. The definition of critical and uncritical situations is also derived from the analysis of experimental data.
Any VSC has to fulfill two criteria: it has to be able to detect critical situations and it has to be able to prevent or mitigate them. Methods to detect the addressed critical situations are developed from the mathematical model. To check if these methods can distinguish critical from uncritical situations, they

are validated with data from the experiments and simulations (critical) and with data from various uncritical test rides.
Methods to influence motorcycle dynamics are also derived from the mathematical model and evaluated regarding physical feasibility and technical feasibility. With assessed methods for detection and prevention of critical situations, the question is answered if and how future vehicle stability control systems can help prevent accidents.

Accident analysis

The objective of the accident analysis is to find accident types that cannot be influenced by today's vehicle stability control systems ABS and TCS (Traction Control Systems). To achieve this, motorcycle experts were questioned about their own experiences with motorcycle accidents (not surprisingly, almost all experts experienced at least one accident). Because of their experience with motorcycles as well as their knowledge of physics, they are able to give a technical explanation of what happened during their accidents. This source delivers around 60 detailed descriptions.
Additionally, around 60 accidents originating from the accident database of the German Insurances Association (*Gesamtverband der Deutschen Versicherungswirtschaft*, GDV) are analyzed. The accident datasets are classified as 'preventable' (the rider reacted before the vehicle collided with the opponent or the road) and 'not preventable' (no reaction). Preventable accidents are further divided into the subgroups 'with today's technology' (ABS or TCS could have prevented the accident but were not available on the motorcycle) and 'with future technology' (unbraked accidents).
The share of those identified accidents on the total amount of motorcycle accidents then is checked with a detailed analysis of all accident datasets from the GDV database (around 900 accidents, representative for Germany). For more information on the accident analysis, refer to [20].
The high risk accident types classified as preventable by future VSC systems are unbraked cornering accidents due to a step of friction (μ-step, accident type 1) and due to exceeding maximum lateral acceleration (e.g. trying to ride at a roll angle larger than the maximum roll angle determined by the road surface, accident type 2).
Their share on Germany's high-risk motorcycle accidents is estimated to be 4 to 8%.

Test Motorcycle

The test motorcycle is a BMW R 1150 RT motorcycle (Figure 1), the motorcycle that was used for the brake tests (see chapter ANTI LOCK BRAKING SYSTEMS). To prevent damage in simulated accidents, it is equipped with a set of outriggers on both sides. The outriggers have Teflon gliders to minimize friction. In order to reduce the influence on the motorcycle inertia to a minimum, they are mounted rotatable to the motorcycle and glide on the ground permanently. If the roll angle exceeds 25°-30° (depending on the state of the Teflon gliders), the motorcycle finds support on the outriggers.
A fiber-optical gyroscope combined with acceleration sensors records the motorcycle's accelerations and angular velocities in all three axes. The accuracy of the roll rate sensor allows calculating the roll angle simply by integrating the roll rate signal. The vehicle's velocity is determined by the production ABS wheel speed sensors, the steering angle is measured by a hall sensor, and a reflex light barrier is mounted to the vehicle.

Simulated accidents

Wet epoxy surface and tarpaulins covered with glue were used to simulate unbraked cornering accidents, for details, see [21]. Both surfaces have a friction coefficient of approximately 0.2. 46 test rides in total were valid. As a variant, on seven test rides additional weight to change the vehicle's center of gravity was mounted.

Table 6.
Number of conducted tests by type and surface

Surface	Type 1 μ-step	Type 2 $a_y > a_{y,max}$
Wet epoxy	7	7
Tarpaulin with glue	28	4

The test layout is shown in Figure 7.

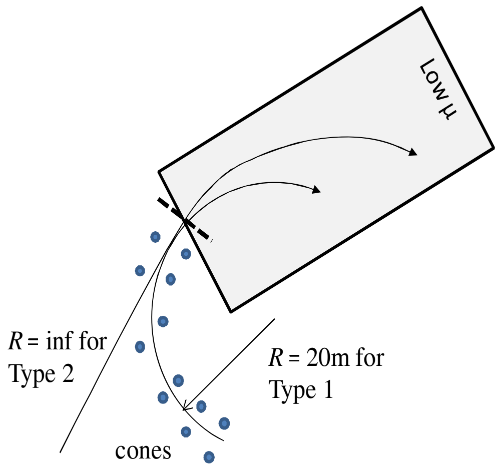

Figure 7. Test layout

For type 1, the vehicle arrives at the low-μ surface with a desired speed between 7 and 8 m/s at a desired turn radius of approximately 20 m at roll angles of 15° to 20°. Capsize of the vehicle occurs almost as soon as it has arrived on the low-μ surface. For type 2, the vehicle arrives with the same speed and a roll angle below 5°.
The objective is to increase the roll angle, once the vehicle has arrived on the low-μ surface, until the vehicle capsizes.
For both simulated accident types, the arrival of the front wheel contact patch on low-μ is detected by the vehicle-mounted light barrier and a calibrated reflector. The impact of the motorcycle on the safety bars is determined by the maximum roll acceleration. Clutch is opened before low-μ-surface.

Computer Simulation

The maximum velocities and maximum roll angles were set by the construction of the motorcycle's safety bars and the size of the low-μ surface. To gather additional data on parameter sets that could not be measured with test rides, a computer simulation software VI/Motorcycle (www.VI-Grade.com) is used. For details on the computer simulation, refer to [20].

Uncritical test rides

Based on the simulated accidents vehicle dynamics data, a criterion for recognition of critical driving situations is developed. Uncritical rides are conducted to provoke failure detection. All rides took place on the "Airfield Griesheim" test track. The test track has an unevenness of a typical German highway [5] and thus is more uneven than the epoxy test track, but all other circumstances were maintained to ensure comparability in between simulated accidents on either surface and uncritical test rides.

Vehicle behaviour in simulated accidents

As mentioned before, two types of accidents have been chosen as the most relevant for future vehicle stability control systems. Both are unbraked cornering accidents, one is caused by a drop of the road friction coefficient (μ-step), the other one is caused by exceeding the maximum lateral acceleration and thus capsizing. The feasibility of vehicle stability control systems to prevent those accident types will be evaluated. This is achieved by simulating the accident types in real-world experiments and computer simulations and developing a mathematical model from the gathered data.

The vehicle behaviour is depicted in Figure 8 for four exemplary test rides: one per surface type (epoxy or tarpaulins) and one per accident type (μ-step or exceeding maximum lateral acceleration). Type 1 accidents have a shorter duration compared to type 2 accidents. For accident type 1, the front wheel starts to slide as soon as it reaches the μ_{low}-surface. The front wheel side force decreases immediately to the value determined by the friction coefficient, the vehicle starts to capsize, see roll velocity, time t=0s. The rear wheel arrives 0.2 seconds later. At that time, the rear wheel side force also drops, the roll velocity increases. The unbalanced side forces of front and rear wheel lead to a yaw momentum and thus a yaw velocity between 0s and 0.2s. The vehicle turns to the outside of the bend. After approx. t=0.2s, the vehicle movement is inverted – it turns to the inside of the bend, until a short time later the vehicle impacts on the safety bars.
For accident type 2, the side forces drop to the sliding value both at the same time. The roll rate increases constantly. No yaw movement to the outside of the bend is observed; instead the vehicle turns to the inside just before the fall occurs (see the last 0.3 seconds). For both cases, pitch movement can be neglected.
The lateral acceleration drops to a level equal to g x μ when both wheels are sliding (after 0.2 seconds for type 1 respectively at the last 0.3 seconds for type 2). The "over-steering" yaw movement observed for the last few 0.1 seconds of both cases therefore cannot be explained by a turn. It can be explained by a slip angular velocity – the vehicle yaws but does not change its course in the same way.
[22] describes an "over-steering" yaw movement during "low sider" type accidents due to a decrease in rear wheel side force. However, the accidents described there are braked accidents – the conclusions cannot be transferred to the accident types this paper focuses on.

Detection of critical driving situations with focus on future VSC systems

With the mathematical model, the vehicle dynamics for critical situations are understood. Methods for detection and avoidance or mitigation of these accident types can be evaluated. If an accident type can be detected as well as prevented, a vehicle stability control system for this accident type is feasible.
The mathematical model of the vehicle behaviour shows that the vehicle side-slip angular velocity is unstable for critical driving situations of the type investigated here (non-braking cornering

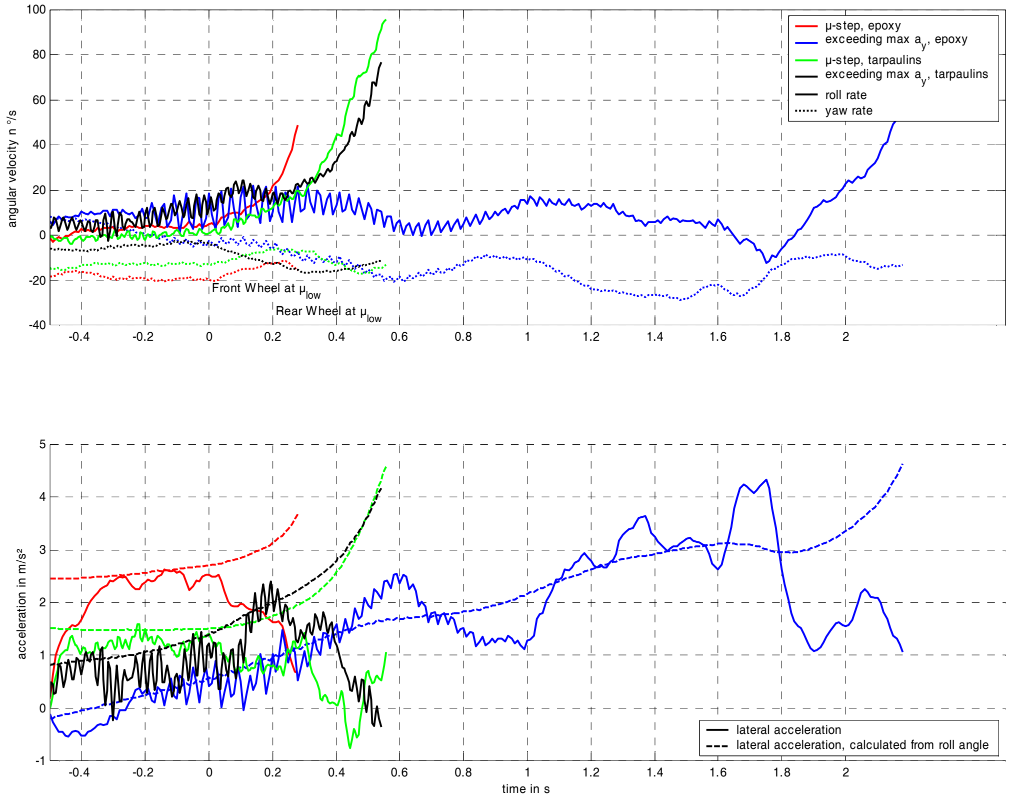

Figure 8. Vehicle behaviour during simulated accidents. All data filtered with first order low-pass filter, 10 Hz cutoff frequency. Lateral acceleration additionally smoothed. Signal vibrations are caused by engine excitation and resonance effects of the rear frame and vanish for idling engine. Pitch rate is neglected.

accidents). General motorcycle tire properties suggest the tire slip angle is always small <1° (refer to [23]), as well as the vehicle side-slip angle. The side-slip angular velocities (both tire and vehicle) are also assumed to be low.

A criterion for the detection of critical driving situations would be

$$\dot{\beta} > \dot{\beta}_{\max,stable} \qquad (5)$$

This criterion can be used to detect critical driving situations, if it fulfills the following two conditions:

- it does detect a simulated accident in all valid test rides (no false-negatives),
- it does not detect an accident in all uncritical test rides (no false-positives).

The side-slip angular velocity of the vehicle cannot be measured directly, it has to be calculated from other measurands. Using the lateral acceleration horizontal to the road plane, the vehicle side-slip angular velocity is

$$\dot{\beta} = \dot{\psi} + \frac{\ddot{y}}{\dot{x}}, \qquad (6)$$

for details on the calculation of the lateral acceleration see [21] and [20].

Figure 9 shows the time of detection for all simulated accidents as cumulative probability distribution. The time is between 0% (front wheel has reached the low-μ surface) and 100% (impact on safety bar). No false-negatives are observed. The majority of simulated accidents was detected in the

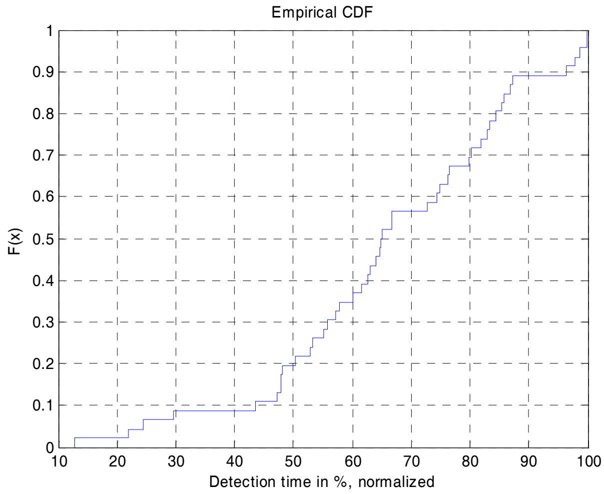

Figure 9. Results: Cumulative Distribution Function for detection of simulated accidents, time normalised with respect to critical situation duration.

last quarter of the critical driving situation duration. However, a value of 100% only means the vehicle has reached the safety bars, not the vehicle has crashed. The safety bars limit the roll angle to values of 25° to 30°. In reality, motorcycles can reach maximum roll angles of up to 55° without crashing, thus giving any control system more time to react.
The ability of the described criterion to distinguish critical and uncritical driving situations is proved, if no false-positives can be found at all. Table shows the types of uncritical test rides.
Using this experimental evidence, the criterion "side-slip rate" has proved the ability to detect critical driving situations. No side-slip rates higher than 0.15 rad/sec + estimated error have been observed for uncritical situations.
These thoughts lead to the following control objectives:

- First, the roll movement has to be stabilized.
- Second, the rear wheel side-slip angle has to be zero for the case of a sudden increase of the friction coefficient.
- Third, if a capsize is inevitable, the vehicle has to turn into the bend.

Table 7.
Description of uncritical ride tests.

	Description	Parameters
1	steady-state cornering	turn radius 9 and 14m $a_{y,0}$ from 0.1 to 0.5g
2	corner braking	turn radius 9 and 14m $a_{y,0}$ from 0.1 to 0.5g
3	swerving	
4	double lane change according to VDA	velocity from 70 to 85 km/h

Possible methods to change the movement of a motorcycle

The accidents focused by this paper involve an unstable yaw movement and an unstable roll movement. Unstable roll movement limits the duration of the accident – as soon as the vehicle hits the ground, a crash occurs. The primary focus should be on the roll stabilization.
If the vehicle capsizes and the surface friction coefficient does not change, it makes no sense to change the yaw momentum. As the motorcycle turns into the bend, the rider falls behind the vehicle. The friction coefficient of today's motorcycle clothing is higher than that of a capsized motorcycle. The motorcycle's deceleration is lower, the distance between motorcyclist and vehicle will increase during the accident.
If the friction value raises again during the tumble, e.g. if the road was slippy only in a small area, a high wheel side-slip angle on the rear wheel will almost instantly cause a high side force on that particular wheel, a dangerous "highside" type accident (which is a fast roll movement of the motorcycle away from the bend direction) would be the consequence.
In order to change the movement of a motorcycle,

- the tire side-slip angles, camber angles or longitudinal slip can be changed,
- the wheel load can be changed,
- gyroscopic effects can be utilized,
- aerodynamic effects can be used.

Roll stabilization

Unstable roll movement can be stabilized by changing the roll momentum, e.g. increasing the sum of side forces and thus the lateral acceleration or applying an additional roll torque to the motorcycle.
As long as one wheel has not reached its maximum side force (e.g. the rear wheel is still on high-μ), changing the tyre properties can increase the side force. The delay between applying a wheel side-slip angle and the resulting side force is dependent on a distance called "relaxation length", for typical tyres this value lies at approx. 0.2 to 0.5 meters [24], for camber changes the delay is negligible. From a physical point of view, stabilization seems to be possible. What needs to be taken into account is the time demand for applying the changed tyre properties. A change of side-slip angle by a rear-wheel steering system is the better choice because the ratio between angle and side force is approximately 10 times higher for side-slip angle than for camber angle. However, the absolute time lag between front wheel and rear wheel (wheel base divided by vehicle speed) is as low as 0.2 seconds for speeds as low as 7 km/h and decreases with 1/velocity. It is doubtable that this short time span is enough for detection and reaction by a technical system.
Roll momentum on a motorcycle with sliding wheels cannot be applied by changing wheel load, using gyroscopic effects or aerodynamic effects, for details, see [25].
Gyroscopic effects can stabilize the roll movement of a vehicle. This is proved by technical examples like the Ford Gyron prototypes [26]. The Ford Gyron prototype cars used a stabilizer gyro with a weight of 180 pounds. Calculations show stabilizer gyroscopes for today's motorcycles would still not be feasible due to large mass, high rotational velocity and control issues. Gyroscopic effects of

the motorcycle's wheels are far too low to stabilize the roll movement.
Aerodynamic effects are an option for capsuled motorcycles, but most probably will not work with standard motorcycles due to the bad aerodynamics.

Yaw stabilization
Side-slip angles, camber angles and longitudinal slip can change the direction of the tyre forces of a sliding wheel (which has reached its maximum side force), but the maximum value cannot be influenced – it is determined by the friction coefficient between tire and surface and the wheel load. These methods therefore can be used to change the yaw momentum to stabilize the yaw movement of the motorcycle.
The accidents that can be mitigated by this method are only a subset of the mentioned 4-8 % of all German motorcycle accidents. For more details, see [20] and [21].

CONCLUSION

Braking is one of the most difficult-to-control motorcycle manoeuvres because the rider has to control two independently operating braking circuits and the motorcycle is stabilized by side and gyro forces. ABS and combined braking systems are designed to support riders while braking. Further dynamic vehicle stability control systems for powered two wheelers besides traction control systems are not known up to now.
Several research projects therefore were carried out to determine possible safety benefits of ABS and VSC for motorcycles.
Test persons were assigned braking tasks with five different brake systems: standard and combined brake system with and without ABS in each case and ABS combined brake with single-lever operation. The stopping distances achieved as well as workload and stress variables for the rider were recorded.
The stopping distances achieved are shorter with ABS than they are without ABS. This also and primarily applies to braking when cornering. It was not possible to establish any significant difference between standard and combined brake. Operation of a combined brake with ABS and with only one brake lever did not show any disadvantage by comparison with a two-lever brake control system. In the case of braking operations without ABS, stress and strain for the rider were significantly higher than in the case with ABS.
In principle, ABS is seen to have the potential to reduce fatalities among motorcycle riders by about 10 %. A socio-economical analysis yielded benefit-cost-ratios of above 4 for motorcycle ABS indicating that this system is highly economically sensible.
ABS thus should be used on all two-wheeled vehicles wherever possible. The ABS system may be designed as a disengageable system.
To assess the technical possibilities for future vehicle stability control systems for motorcycles and the amount of accidents that could be prevented by those systems an accident analysis was carried out. Accidents while cornering without braking have been determined as potentially avoidable by future technical systems. The accidents can be caused by low friction or by raising the lateral acceleration over the possible maximum. About 4 to 8 % of all motorcycle accidents are of this type. Both accident types have been analyzed with driving experiments and computer simulation. The vehicle sideslip angle speed proved to be a robust criterion for recognizing whether a driving situation is critical.
Possibilities for technical systems to influence the critical driving situations were estimated. The roll movement of the vehicle cannot be influenced, because neither the tire side force can be increment-ted nor stabilizing gyroscopes can be built small enough. The vehicle sideslip angle speed can be influenced by braking the front or the rear wheel, thus generating a yaw moment to avoid the dangerous high-side type accidents at friction steps from low to high. The motorcycle accidents influenced by this system are only a subgroup of the mentioned 4 to 8 % of all accidents, so as a result of this study, the potential for future dynamic control systems is estimated very low. Making them mandatory can-not be recommended at present. Further research with regard to driving stability of motorcycles should rather focus on active damping devices.

REFERENCES

[1] Weidele: „Untersuchungen zum Bremsverhalten von Motorrädern unter besonderer Berücksichtigung der ABS-geregelten Kurvenbremsung." Diss. TH Darmstadt, Fortschritt-Berichte VDI, Reihe 12, Nr. 210, VDI Verlag, Düsseldorf 1994

[2] Ecker, Wasserman, Ruspekhofer, Hauer, Winkelbauer: "Brake Reaction Times of Motorcycle Riders." In: Proceedings of the 3rd International Motorcycle Safety Conference, Orlando 2001

[3] Sporner: „Bremsen als Todesursache! Erkenntnisse der Unfallforschung der Deutschen Autoversicherer." In: Neue Aspekte der Fahrzeugsicherheit bei Pkw und Krad. Tagungsband zur BAIS Frühjahrstagung 2003, Books on Demand Verlag, Norderstedt 2003

[4] Schmieder, Bley, Spiekermann, Zettelmann: „Kraftschlußpotentiale moderner Motorradreifen." Berichte der BASt, Reihe 12 Fahrzeugtechnik, Heft F9, Bergisch Gladbach 1994

[5] Niemz, T.: "Reducing braking distance by control of semi-active suspension." Düsseldorf: Als Ms. gedr. Aufl. VDI-Verl, 2007. - 978-3-18-364012-6

[6] Kerwien, Ruhdorfer: „Subjektive Sicherheit bei Rennstreckentrainings für Motorradfahrer." In: Tagungsband der 3. Internationalen Motorradkonferenz 2000, Forschungshefte Zweiradsicherheit Nr. 9 des Instituts für Zweiradsicherheit, Essen 2000, S. 135

[7]: Funke: „Dynamische Vorderradüberbremsung bei Motorrädern." TU Darmstadt, Fachgebiet Fahrzeugtechnik, Bericht Nr. 270/00, Darmstadt 2000, excerpts published in: Sporner: Neueste Ergebnisse der Unfallforschung der Deutschen Autoversicherer mit speziellem Schwerpunkt: Bremsen mit Motorrädern. In: Tagungsband der 4. Internationalen Motorradkonferenz 2002, Forschungshefte Zweiradsicherheit Nr. 10 des Instituts für Zweiradsicherheit, Essen 2002

[8] Funke: „Belastung und Beanspruchung von Motorradfahrern bei der Bremsung mit verschiedenen Bremssystemen." Diss. TU Darmstadt, Fortschritt-Berichte VDI, Reihe 12, Nr. 633, VDI Verlag, Düsseldorf 2007, URL: http://tuprints.ulb.tu-darmstadt.de/epda/000907/Funke_Joachim_FZD_Diss.pdf, seen at 30.01.2009

[9] Präckel: „Die Motorradbremsung im System Mensch / Maschine / Umgebung." Diss. TH Darmstadt, Fortschritt-Berichte VDI, Reihe 12, Nr. 384, VDI-Verlag, Düsseldorf 1999

[10] Böse: "Smart Fluids for Semi-Active Damping Systems." In: Proceedings of the 3rd Advanced Suspension Systems Conference, Wiesbaden 2008

[11] Savaresi: "Future of Semi-Active Suspensions in Motorcycles." In: Proceedings of the 3rd Advanced Suspension Systems Conference, Wiesbaden 2008

[12] Assing, K.: „Schwerpunkte des Unfallgeschehens von Motorradfahrern." Berichte der Bundesanstalt für Straßenwesen, Heft M 137, Bergisch Gladbach 2002.

[13] INFRAS/IWW: "External Costs of Transport", Update Study, Final Report, Zürich/Karlsruhe, 2004.

[14] Baum, H. et al.: „Cost-benefit analysis for ABS of motorcycles", Berichte der Bundesanstalt für Straßenwesen F 68, Bergisch Gladbach 2008.

[15] CONTI-TEVES: Press report on the occasion of the INTERMOT 2004.

[16] Sporner, A.: „Neueste Ergebnisse der Unfallforschung der Deutschen Autoversicherer mit speziellem Schwerpunkt: Bremsen mit Motorrädern." 4. Internationale Motorradkonferenz München 2002

[17] STATISTISCHES BUNDESAMT: „Verkehr – Zweiradunfälle im Straßenverkehr 2005", Wiesbaden, 2006.

[18] Orth, M.; Sorg, N.: „Technik für Quiddelbacher: ABS, Teil zwei – Einfach kompliziert", in: Motorrad, issue 26, Stuttgart 2005.

[19] BASt: „Volkswirtschaftliche Kosten durch Straßenverkehrsunfälle in Deutschland 2004", URL: http://www.bast.de, Publikationen/ Fachliche/Infos/2007.

[20] Seiniger, P.; Winner, H.: „Objektive Erkennung kritischer Fahrsituationen von Motorrädern im Hinblick auf eine Fahrdynamikregelung für Motorräder." Bericht für das Forschungsprogramm Straßenverkehrssicherheit der Bundesanstalt für Straßenwesen, 2007.

[21] Seiniger, P.; Winner, H.; Gail, J.: "Future Vehicle Stability Control Systems for Motorcycles with Focus on Accident Prevention." ASME Conference on Engineering Systems Design and Analysis, Haifa, Israel: 2008.

[22] Cossalter, V.; Aguggiaro, A.; Debus, D.; Bellati, A.; Ambrogi, A.: "Real Cases Motorcycle and Rider Race Data Investigation: Fall Behavior Analysis." 20th Int. Conference ESV, Lyon 2007.

[23] Weidele, A.: "Motorräder." Course at TU Darmstadt, Darmstadt 2005.

[24] Cossalter, V.: "Motorcycle dynamics." Greendale, WI: 1st English ed. Race Dynamics, 2002.

[25] Seiniger, P.; Winner, H.: "Potential of Active Suspension Systems for Vehicle Stabilization." IfZ Motorcycle Conference, Köln, Germany, 2008.

[26] Hibbard, R.; Karnopp, D.: "Twenty First Century Transportation System Solutions - a New Type of Small, Relatively Tall and Narrow Active Tilting Commuter Vehicle." In: Int. J Veh. Sys. Dynamics 25 (1996), S. 321-347

MAINLAND EUROPEAN TRUCK ACCIDENTS IN THE UK - KEY ISSUES FOR DRIVERS

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ABSTRACT

The native UK vehicle fleet is right hand drive (RHD) with a corresponding road infrastructure, presenting unique challenges to the increasing numbers of mainland European left hand drive (LHD) heavy goods vehicles (HGVs) using UK roads. This paper analyses the nature and circumstances of HGV accidents in the UK, paying particular attention to LHD HGVs and the causal factors exhibited.

Using in-depth real world accident data the characteristics of 65 LHD HGVs involved in accidents are described in comparison with 250 RHD HGVs. On-scene cases from the UK 'On The Spot' (OTS) project, funded by the UK Department for Transport and Highways Agency, enable a detailed examination of accident causation mechanisms and behavioural patterns. Comparison is made with the national accident data to put the in-depth investigation into context.

The majority of LHD HGV collisions include causal factors related to vehicle geometry (blind spots) and driver mental load, compared to RHD HGV collisions which include injudicious and road environment factors. Discussion focuses on the complex, multifactorial nature of these accidents with both vehicles and drivers not best adapted for UK roads. Key aspects of the accidents studied are identified and their implications are discussed for enhanced driver support and education.

There are inevitable limitations regarding the amount of detail that can be collected on-scene due to the time consuming nature of the specialist vehicle examinations required and the language barrier. A pilot, translated, interview procedure has however been put in place to gain the maximum amount of information.

INTRODUCTION

As the European Union and particularly the commercial trade between the member states continues to grow, so does the concern regarding foreign heavy goods vehicles (HGVs), or specifically Left Hand Drive (LHD) HGVs using UK roads, making a review of the scientific evidence timely. This paper reviews real world accident data in order to identify common accident scenarios for LHD HGVs and compares these to accidents involving Right Hand Drive (RHD) HGVs. This gives an indication of driving issues faced by foreign drivers on UK roads. It is not the aim of the paper to apportion blame to any group of drivers.

As is the case in many road traffic accidents all parties involved contribute to the accident to some degree through driver experience or behaviour. However this paper is heavily biased towards looking at HGVs and their contribution to the accident and although the collision partner may have also played a causal part in the whole accident, this has not been reviewed.

After considering the overall picture using British national data this paper utilises the information gathered by the On The Spot (OTS) project.

This paper is a first examination of the challenges faced by LHD HGV drivers when driving on the left hand side of the road. It offers guidance to LHD HGV drivers on avoiding accidents whilst making native UK drivers more appreciative of the difficulties. Consideration is given to the benefits of new technologies while also taking into account possible increases in driver distraction.

LITERATURE REVIEW

Blind Spot Areas

Inevitably, heavy goods vehicles, due to their size and geometric make up, suffer from vehicle blind spots that are far larger and more obtrusive to the driver than the average car driver, a problem that is exaggerated when left hand drive vehicles travel on the left side ("wrong" side) of the road in the UK.

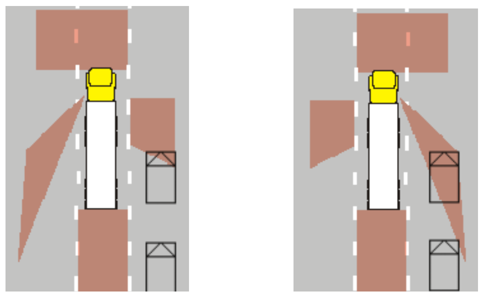

Figure 1. Possible blind spots for HGV drivers

Figure 1 illustrates the typical blind spot areas to be found on both LHD and RHD HGVs. It demonstrates the effect of a car overtaking a HGV and how the car is obscured by a blind spot for the LHD HGVs.

According to the Royal Society for the Prevention of Accidents (RoSPA) (2007)[1] the larger blind spot that results from using a left hand drive vehicle on British roads is the most obvious safety concern. This problem is most pronounced when other road users pass on the far side of the vehicle, and for right turning vehicles.

During a trial conducted by the UK Vehicle & Operator Services Agency (VOSA) in 2007, 40,000 'fresnel lenses' were distributed to LHD vehicles entering the UK at Dover. The lenses are small sheets of flexible plastic with a moulded lens which adheres to glass and help to alleviate the problem of the LHD truck blind spot. It was estimated that there was a 59% decrease in side-swipe incidents as a result of the lenses[2].

Background Statistics

In 2003 the UK Department for Transport (DfT) stated there had been a 150% increase between 1992 and 2003 in the number of LHD HGVs using British roads each day. By 2005 it was anticipated that there would be an estimated 10,000 LHD HGVs using British roads each day[3].

In 2005 the British national accident data (STATS19) recorded 1,164 injury accidents which were classed as side-swipe collisions. Of these accidents 39% involved LHD or foreign registered HGVs, the majority of these accidents occurred as the HGV changed lanes to the right[4].

According to data collected by UK Police in Kent[5], there were 333 accidents in that area between 1994 and 2001 where the cause was a LHD HGV changing lanes to the right.

Legislation

Since the issue of relevance here is HGVs which are not primarily registered or operated in the UK it is European legislation that is most relevant. In general, legislation aimed at the safety of HGVs has been relatively limited. The exception to this is the 2003 European directive which requires all new HGVs (vehicles with a weight of more than 3.5 tonnes) to be equipped with blind spot mirrors[6]. However, since replacement of the truck fleet in Europe is relatively slow, it was estimated that the fleet would only be fully replaced by 2022 at the earliest. It was estimated that introduction of a legal obligation to retrofit mirrors to vehicles in operation since 1998 would save an additional 1,300 lives in Europe up to 2020.[7]

The Causes of Truck Accidents

According to the European Truck Accident Causation study (ETAC)[8] the main cause of truck accidents is linked to human error in the majority of cases (85.2%), with other factors (for example, vehicle, infrastructure or weather) playing a minor role. Accidents due to lane departure and accidents after an overtaking manoeuvre – probably the two configurations of most relevance here – were responsible for 19.5% and 11.3% of the accidents respectively. However investigations were not done in the UK.

Another significant factor in goods vehicle accidents is fatigue. A study by RoSPA[9] using data from 2001 estimated fatigue to be a factor in 16 to 23% of motorway accidents and 11% of HGV and Public Service Vehicle (PSV) accidents.

General Issues

There are a number of issues which might be predicted to influence the accident involvement of foreign drivers, regardless of where they are from or which roads (besides those in their country of origin) they are driving on. Yannis et al (2007)[10] provide an extensive list of factors, including:

- poor knowledge of the road network;
- lack of understanding of the local rules;
- insufficient driving skill;
- variance of attitudes, reflected in driving behaviour.

As well as the obvious difficulty of driving on the opposite side of the road, there are a number of additional factors which may make the UK a particularly problematic place for non-native drivers to operate safely. RoSPA (2007) highlights:[1]

- the imperial system, leading to problems understanding distances and speed limits;
- the unique treatment of HGVs compared to other classes of road user, meaning that the posted limit may be higher than the limit which applies to HGVs.

Increased Mental Load

Yannis et al (2006)[10] highlights the potential of increased mental load as a contributory factor in accidents involving foreign drivers, since certain road characteristics are found to significantly differentiate the risk between different nationalities. Inhabited areas and junctions are two such characteristics. Yannis et al conclude that,

"This may be attributed to the fact that urban areas and junctions require a more demanding driver behaviour, namely a combination of decisions under more complex traffic conditions and more traffic rules".

Vehicle Factors

According to RoSPA (2007)[1] the UK has the most stringent vehicle maintenance standards in Europe. Vehicles which would be deemed unsafe by UK standards may be able to use the UK road network. This view appears to be supported by figures published by the UK Vehicle and Operator Services Agency (VOSA)[11] which found that half of the foreign lorries checked in 2006 had serious vehicle defects which could have affected their safety. In addition, one third of vehicles from Spain, Portugal and the Republic of Ireland were found to be overloaded.

METHODOLOGY

The main focus of this study was perform a review of the nature and circumstances of accidents involving LHD HGVs by comparing typical scenarios with those involving RHD HGVs. This was achieved by analysing the British national accident data (commonly called 'STATS19' after the form that is completed by the Police)[4] and then in-depth OTS accident dataset was analysed focussing only on HGVs. For the purposes of this study, the issue of interest is defined as LHD HGVs with drivers who are less familiar with the language, road network and general traffic conditions.

There are two investigation teams working on the OTS project, the Vehicle Safety Research Centre (VSRC) at Loughborough University, working in the Nottinghamshire region and the Transport Research Laboratory (TRL), working in the Berkshire region. The OTS teams attend and investigate, in total, 500 real-world collisions per year on a rolling shift pattern, covering all times and days of the week. The OTS teams investigate all collision types including all road users, all injury severities (from non-injury to fatal) and all road classifications. While OTS is not intended to function as a specialist HGV accident study, investigations include vehicle examinations, road-user interviews and reconstructions as for all other road user types encountered. Both teams work in slightly different road network areas, which collectively are broadly representative of the UK. The study has been running since 2000 and at the time that this analysis was carried out had investigated over 3,500 real world collisions. The detailed methodology has been described elsewhere by Hill et al. (2001[12] and 2005[13]).

All accidents involving an HGV were reviewed to identify causation factors and trends across a range of collision scenarios. After initial examination of the cases, the sample could be split into LHD and RHD HGVs, allowing specific collision scenarios and common occurrences to be identified.

The data was further analysed to compare and contrast scenario types between LHD and RHD HGVs. Basic collision conditions were compared, before moving onto the more complex data available relating to the causes of collisions.

OTS utilises a variety of advanced systems for evaluating causation of which three are explored in this paper: Accident Causation System; Contributory Factors 2005 and Human Interactions.

Injury severity is shown as fatal, serious, slight or non-injury according to the UK police classification.[4]

RESULTS - STATISTICAL ANALYSIS OF BRITISH NATIONAL DATA (STATS19)

Analysis of the accident causation factors commonly attributed to HGV drivers is presented here, as a complement to the more in-depth (OTS) analysis to follow.

HGV Occupant Casualties in the National Data

Examining the British national accident data for 2006 there are 2,172 accidents that involved injury to an occupant of an HGV.

The number of occupant casualties is lower for LHD foreign registered HGVs with 66 reported casualties, 3% of the figure for other HGVs (2,464).

Accidents with HGVs Involved - Casualty Severity

Due to the size of HGVs in relation to most collision partners it is appropriate to consider the number of accidents with at least one HGV involved and the resultant casualties in the entire accident. Table 1 gives the number of accidents by the overall accident severity for different combinations of HGV involvement.

Table 1.
Accidents with HGV involvement – Great Britain 2006

Accidents with:	*Fatal*	*Serious*	*Slight*	*Total*
Any HGV involved (A or B)	*386*	*1,445*	*8,635*	*10,466*
A involved	*30*	*77*	*845*	*952*
B involved	*367*	*1,381*	*7,849*	*9,597*

Key:

Foreign registered LHD HGV	*A*
Other HGVs	*B*

It is clear from Table 1 that HGVs are involved in many more injury accidents than there are HGV occupant casualties. Of the 10,466 injury accidents involving an HGV, only 2,172 (21%) involved injury to an occupant of an HGV.

Overall, 9% of all reported HGV accidents involved a foreign registered LHD HGV, which is 0.5% of the total 189,161 injury accidents recorded for 2006.

Contributory Factors for HGV Drivers in the National Data

The Contributory Factors 2005 system has been adopted nationally by police forces since 2005 and completed for all police reported collisions, with data on injury accidents reported in STATS19.

The Contributory Factors 2005 code can be assigned with a confidence level of 'very likely' or 'possible', both are included here. There can be a maximum of 6 codes assigned to each collision therefore a single vehicle could have multiple codes assigned to it. For this reason in the results presented below the total number of codes is a higher figure than the number of vehicles. Only accidents where a police officer attended the scene are included in this section of analysis. This follows the official Government practice followed in the contributory factor analysis included in Road Casualties Great Britain[14].

Table 2 shows the proportion of HGV drivers who have a contributory factor recorded for them.

Table 2.
HGV drivers who have at least one contributory factor attributed to them – Great Britain 2006

Driver of:	*No Factor*	*At least 1 Factor*	*% with Factor*
Foreign registered LHD HGV	*206*	*722*	*78%*
Other HGV	*4,296*	*4,914*	*53%*

From Table 2 it is clear that when LHD foreign registered HGV drivers are involved in some way in an accident they are more likely to have a contributory factor attributed to them than other HGV drivers, 78% compared to 53%.

Figure 2 gives the proportion of drivers with at least one contributory factor associated with them who have a certain factor attributed to them. So, for example, 48% of LHD foreign registered HGV drivers, with at least one factor associated with them, are recorded as 'failing to look properly'.

Only the top 14 most common factors are illustrated for clarity.

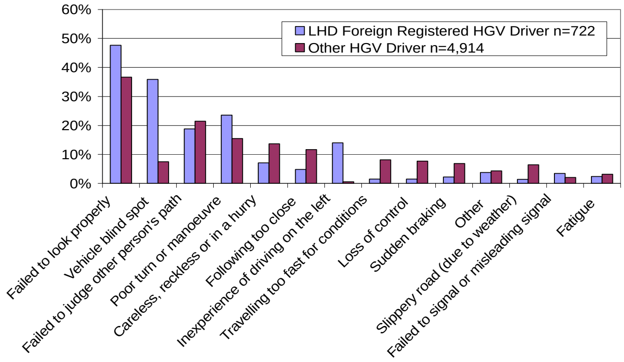

Figure 2. Proportion of drivers with at least one contributory factor attributed to them - most frequent factors – Great Britain 2006

It is clear that 'vehicle blind spot' and 'inexperience of driving on the left' feature distinctively for LHD foreign registered HGV drivers and a higher proportion of them have 'failed to look properly' or made a 'poor turn or manoeuvre' attributed to them than other HGV drivers. It is likely that it is these factors that are influencing the higher proportion of all LHD foreign registered HGV drivers who have at least one contributory factor attributed to them.

The proportion of LHD foreign registered HGV drivers with 'fatigue' attributed to them is smaller at 2.4% than the corresponding figure for other HGV drivers at 3.1%.

The contributory factor system includes 6 factors addressing vehicle defects. These are considered in Figure 3 as the literature review highlights strong preconceptions regarding the poor maintenance and safety of foreign vehicles.

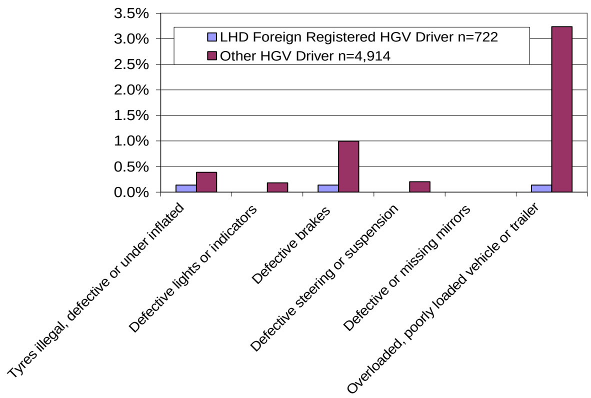

Figure 3. Proportion of drivers with at least one contributory factor attributed to them by 'vehicle defect' factors – Great Britain 2006

Although the proportion of HGV drivers that have a vehicle defect contributory factor attributed to them is small there is a marked difference between LHD foreign registered HGV vehicles and other HGVs. In each of the six categories the percentage for LHD foreign registered HGV vehicles is less than for other HGVs. There is a very large difference for the 'overloaded or poorly loaded vehicle or trailer' factor.

Accidents with HGVs Involved - Road Class using National Data

The following analysis considers the road classification of the accident site for injury accidents involving HGVs with at least one contributory factor assigned.

Figure 4 compares the road classification distribution for accident involvement between the two types of HGV defined in this analysis. Unfortunately it is not possible to differentiate between trunk roads, which is possible with the OTS dataset.

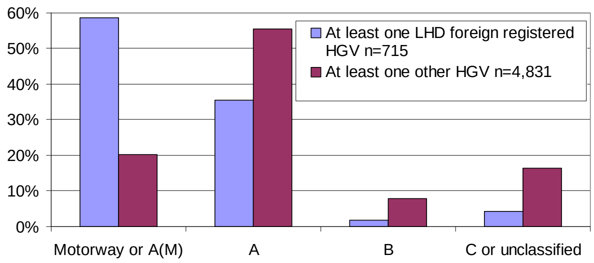

Figure 4. Road classification vs. HGV type (at least one causation factor attributed to HGV) – Great Britain 2006

It is clear that injury accidents which involve at least one LHD foreign registered HGV occur proportionally more often on motorways and less often on A roads than those accidents involving at least one other HGV. Generally LHD foreign registered HGVs are involved in proportionally more accidents on motorways and A roads than B, C or unclassified roads with 94% on motorways and A roads. In comparison, this figure is 76% for other HGVs.

RESULTS - OTS DATA ANALYSIS

OTS General HGV Statistics

If an accident involved two HGVs both are included in order to increase the understanding of the causation factors each vehicle has contributed to the accident. This improves the knowledge of HGV accidents and enables a full comparison between LHD and RHD HGVs.

The total number of HGVs and the frequency of OTS accidents (cases) involving HGVs are outlined in Table 3.

Table 3.
Number of HGVs in OTS collisions

Seat orientation	*Number of HGVs*	*Number of accidents*
Left hand drive	*65*	*64*
Right hand drive	*250*	*232*

Only HGVs where the drive orientation was recorded (some vehicles did not stop at the scene and could not be traced) are included in the analysis. Within the sample of HGVs, 20% are LHD and 80% are RHD.

The overall accident severity for accidents involving an HGV is shown in Table 4 by the type of HGV, LHD or RHD. This injury severity may not have been the injury outcome for the driver of the HGV but is the highest recorded injury in that accident. Of accidents involving LHD HGVs, 37% are injury accidents compared to 60% of RHD HGV accidents.

Table 4.
Severity of collisions involving HGVs - OTS data

	Severity of all accidents (n=315)				
	Fatal	*Serious*	*Slight*	*Non-Injury*	*n/k*
LHD	*0*	*4*	*20*	*40*	*0*
RHD	*13*	*32*	*92*	*93*	*2*
Total	*13*	*36*	*112*	*133*	*2*

The proportion of collisions involving LHD and RHD HGVs according to the road classification where the collision occurs is shown in Figure 5.

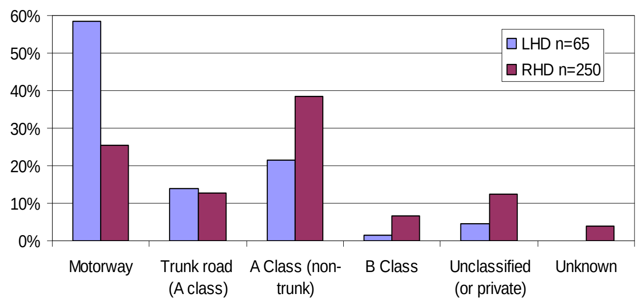

Figure 5. Road classification vs. HGV type

Motorways and trunk roads are broadly compatible with road types found on the Trans European Road Network (TERN). The greater proportion of LHD HGV collisions occur on motorways (59%), followed by A class (non-trunk) roads (22%). Those two carriageway classes also feature in most RHD HGV collisions, but in the reverse order (A class non-trunk 39%, motorways 26%). This observation would be expected as the vast majority of miles driven by HGVs are on the main arterial routes.

During the HGV case review process a judgement was made as to whether the HGV had performed the principal or most significant contributing factor in the collision. This was established by an experienced investigator based on all the causation factors and the strength of confidence given to each factor by the investigation team. This resulted in a subset of cases for both LHD and RHD HGVs where the principal causation factors had been attributed to the HGV and thus enabled the analysis to focus on certain collision scenarios with a high level of confidence. This selection criteria further reduced the sample as shown in Table 5. Only these HGVs are used in the analysis of causation factors.

Table 5.
HGVs performing the most significant causal factor

Seat orientation	*Number of cases*
Left hand drive	*55*
Right hand drive	*138*

Every accident is classified to best describe the type of collision. This discriminates, for example, between rear-end collisions, merging collisions, and loss of control on bends.

Figure 6 shows the distribution of accident types occurring in the sample for both LHD and RHD HGVs.

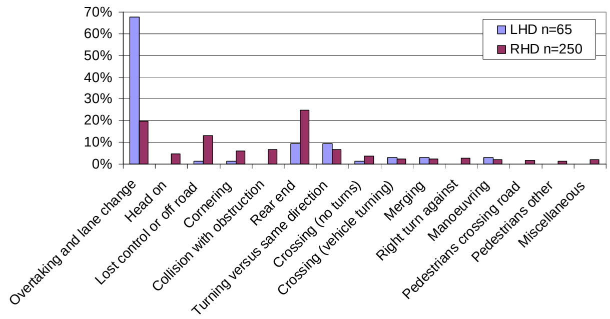

Figure 6. Accident types

The most frequent collision types are "overtaking or lane changing" with the majority of 67.3% (n=37) of LHD HGVs, compared to only 13.8% (n=19) of RHD HGVs. Of RHD HGVs, 30.4% (n=42) are involved in a "rear end" collision, compared to only 7.4% (n=4) of LHD HGV accidents.

In order to understand the different accident scenarios driver types have been split according to the driving action prior to the collision. The term “move to the right” or “move to the left” includes controlled lane changes and swerving actions.

Table 6.
Driver action, movement prior to collision

HGV	Move to right	Move to left	Rear end	Other
LHD (n=55)	47 (85.5%)	2 (3.6%)	4 (7.3%)	2 (3.6%)
RHD (n=138)	9 (6.5%)	27 (19.5%)	39 (28.3%)	63 (45.6%)

The results in Table 6 show that the majority of LHD HGVs move to the right in the OTS sample, with 85.5% performing this manoeuvre, compared to only 6.5% of RHD HGVs performing the same action to the right. It is interesting to note that a larger proportion of RHD HGVs are performing a manoeuvre to the left than right, which may be due to the influence of blind spots.

OTS Accident Causes

OTS utilizes a variety of advanced systems for evaluating the causes of accidents of which three are explored by the present paper:

- Accident Causation system;
- Contributory Factors 2005;
- Human Interactions.

OTS Accident Causation System

The OTS Accident Causation System gives each accident a single precipitating factor. Only one precipitating factor can be selected for each case from a list of 15. The selected factor is the principle causation factor which the investigation team believe directly precipitated the occurrence of the collision.

The analysis of precipitating factors use accidents where the precipitating factor has been linked to the HGV and not any other collision participant.

Figure 7 gives the distribution of the precipitating factors for the 55 LHD HGVs with the precipitating factor in the accident attributed to them.

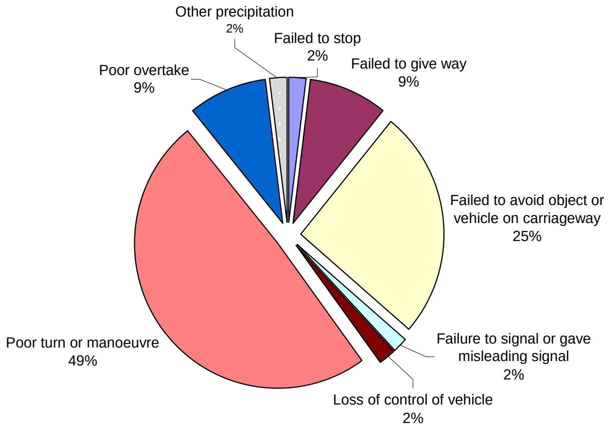

Figure 7. Precipitating factors for LHD (n=55) HGVs

Figure 7 clearly shows the largest proportion, 49%, of LHD HGV collisions are coded as a 'poor turn or manoeuvre' (n=27) and the next most frequent precipitating factor is 'failed to avoid object or vehicle' at 25% (n=14).

Figure 8 gives the distribution of the precipitating factors for the 138 RHD HGVs with the precipitating factor in the accident attributed to them.

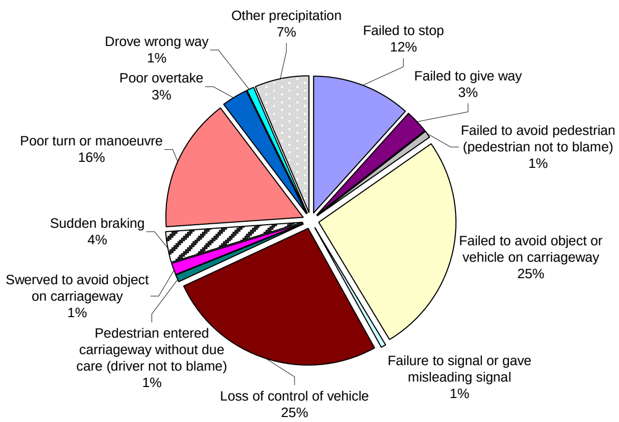

Figure 8. Precipitating factors for RHD (n=138) HGVs

The two largest sub groups in Figure 8 are 'failed to avoid object or vehicle' (25% n=36) and 'loss of control' (25% n=36), the third most frequent factor is 'poor turn or manoeuvre' (16% n=22).

Contributory Factors 2005 Coding System

The OTS project completes the contributory factor codes in isolation from the police investigation in order for the OTS investigation to remain independent.

In order to compare the contributory factors between LHD and RHD HGVs it is important to understand the proportion of HGVs which have been attributed with a factor so they can be included in the analysis. The results in Table 7 are the proportion of LHD and RHD HGV drivers which have at least one contributory factor attributed to them out of the whole HGV sample.

Table 7.
HGV drivers who have at least one contributory factor attributed to them - OTS data

Driver of HGV	*No Factor*	*At least 1 Factor*	*% with Factor*
LHD n=65	*8*	*57*	*88%*
RHD n=250	*96*	*154*	*62%*

It is clear that when LHD HGV drivers are involved in some way in an accident they are more likely to have a contributory factor attributed to them than RHD HGV drivers, 88% compared to 62% respectively.

The distribution of contributory factor codes presented in Figure 9 and Figure 10 gives the proportion of HGV drivers that had a particular factor attributed to them. Figure 9 shows the top 10 factors used by OTS investigators for the LHD HGV accidents. For clarity Figure 10 shows the top 12 factors used by the investigation teams for RHD HGVs.

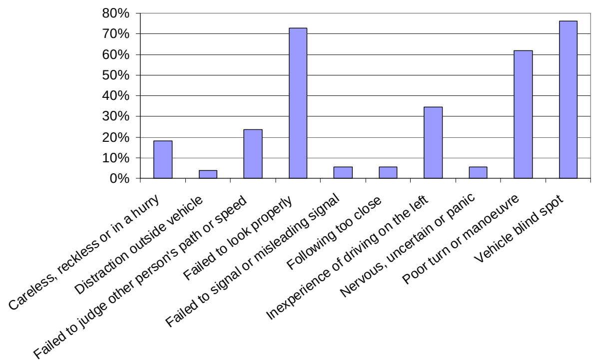

Figure 9. Contributory factors for LHD HGVs (n=55)

For LHD HGVs, the three largest proportions are "vehicle blind spot" 76% (n=42), "failed to look properly" 72% (n=40), "poor turn or manoeuvre" 61% (n=34) and a fourth factor "inexperience of driving on the left" 35% (n=19). The two most frequent demonstrating that the vision the driver is afforded is an issue when driving a LHD HGV on the UK network.

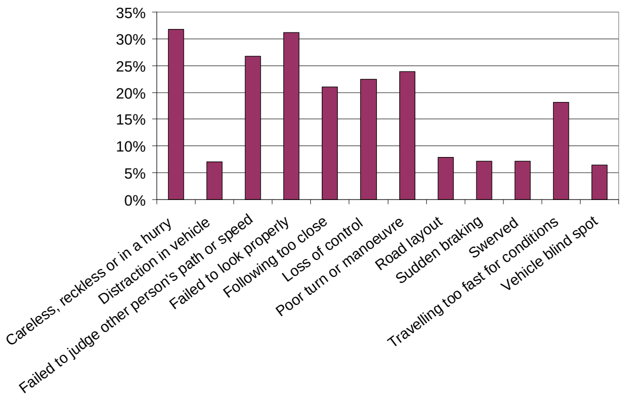

Figure 10. Contributory factors for RHD HGVs (n=138)

The three highest proportions for RHD HGVs are ‘careless reckless or in a hurry’ 32% (n=44), ‘failed to look properly’ 31% (n=43) and ‘failed to judge other person’s path or speed’ 25% (n=34). Although driver vision is still an issue other driver behaviour traits are more frequent for RHD HGVs.

The Human Interactions System in OTS

Each active road user involved in a collision is assigned an OTS Human Interaction Code; this code is used to show how this road user has interacted with other road users, vehicles or elements of the road environment (highway). There are 7 categories of interaction: legal, perception, judgement, external factor, conflict, attention and impairment. These categories are then sub-divided into more specific interaction codes. Each active road user, or in this case driver, will be attributed at least one interaction code but multiple codes can be attributed to the same driver.

Figure 11 and Figure 12 show the most common interaction codes for the LHD and RHD HGVs which have performed the most significant causal factor. As each driver can be assigned several codes, for clarity, only the ten most frequent causal factors have been displayed.

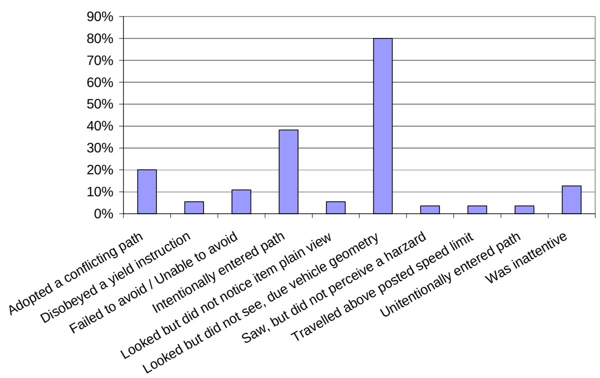

Figure 11. Most frequent interaction codes for LHD HGVs

It can be seen that the most common actions by LHD HGVs are ‘looked but did not see, due to vehicle geometry (e.g. blind spot, windows)’ and ‘intentionally entered into path of (e.g. swerved)’. For LHD HGVs the interaction codes for vehicles’ positioning on the carriageway and driver behaviour are coded frequently, for instance ‘intentionally entered path’ and ‘adopted a conflicting path’.

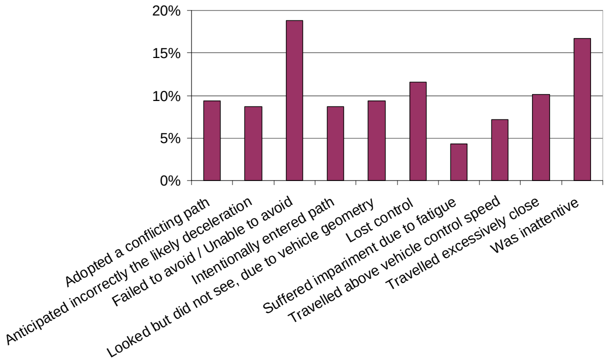

Figure 12. Interaction codes for RHD HGVs

Figure 12 shows that the two actions most commonly indicating driver actions for RHD HGVs are ‘failed to avoid / unable to avoid’ and ‘was inattentive’.

There are higher proportions of interaction codes for RHD HGVs amongst the ‘perception’ and ‘judgement’ categories with codes such as ‘anticipated incorrectly the likely deceleration’ and ‘travelled excessively close to’.

DISCUSSION

This discussion section not only brings together the results of the analyses presented in this paper and considers them in the context of the literature review, but also considers the methodologies involved in the collection of real world accident data involving HGVs.

Number of Cases and Notification Levels

For both databases examined, around 9% involved an HGV of any type. Focusing on LHD HGVs shows they make up 0.5% and 1.8% of accidents on the national and OTS databases respectively. The proportion of OTS investigated accidents involving a LHD HGV is therefore over three times higher than in the national data. This can be explained, at least partially, by the injury selection criteria for each database, as OTS collects damage-only and injury accidents whereas only injury accidents are included in the national data. The police are called to the majority of injury (but not damage-only) accidents and a record is then created on the national database. However, OTS investigators believe that when an accident occurs with a foreign HGV involved, other participants in the accident are more likely to call the police, even if no injury occurs. This is primarily because the potential language barrier doesn't allow an easy exchange of details for insurance purposes. Although the police do not make a record for damage-only accidents, the OTS team are then called to investigate.

Injury Severity

Regarding injury severity the clearest indication of the injury disparity between HGV occupants and other road users is that HGV occupants are only injured in 21% of the injury accidents that they are involved in (Great Britain 2006). This result is understandable given that HGVs are usually much larger than their crash opponents.

Accident Location

Figures from both the national data and OTS show that the majority of LHD HGV accidents occur on the fastest roads. In both datasets over 90% of LHD HGV accidents occur on Motorways or A roads.

With the transportation of freight, large distances are involved so the main arterial routes will see a larger proportion of the distance travelled by HGVs. Therefore just considering exposure by miles travelled will dictate that these roads feature highly in the accident databases. On these types of roads changing lanes frequently, joining and leaving the main carriageway are typical manoeuvres and if blind spots are a feature in HGV accidents then it is not unexpected to find the majority of accidents on these roads.

Accident Types

In the OTS LHD HGV sample the majority, 67%, of HGVs are involved in a collision which was an 'overtaking or lane change manoeuvre' which is understandable considering the type of roads these accidents are occurring on (main arterial routes). This is 3.4 times higher than for RHD HGVs which are split between general driving type scenarios such as 'loss of control', 'shunt accidents', 'cornering' and also 'overtaking manoeuvres'.

When addressing the issue of HGV accidents and especially LHD HGV accidents the issue of blind spots is an important one to consider with the HGV changing lanes to the right and colliding with a vehicle the driver 'didn't see'. The complementing issue for RHD HGVs is overtaking a vehicle and changing lanes into the left or merging lanes. The OTS sample shows that in 85% of the LHD HGV accidents the suspected scenario of changing lanes to the right is the driving action which caused the collision compared to only 20% for the complementing action to the left for RHD HGVs. This suggests that it is not only a blind spot issue but also a driver experience issue of interacting with the road and traffic environment. For example the RHD HGV would have overtaken a vehicle before changing lanes back, therefore the driver should be aware of the vehicle to the left. In contrast to this the LHD HGV is changing lanes to perform an overtake and is aware of the vehicle in front but did not see the vehicle to the right. Additionally, collisions may be more likely because frequency and relative speeds will be greater for vehicles travelling to the right of an HGV.

A large proportion of LHD HGVs, 49%, are involved in a collision where the precipitating factor is 'poor turn or manoeuvre', a category that would also include changing lanes or negotiating junctions. This is much higher than the figure for RHD HGVs with only 16% involved in an accident with this precipitating factor.

Overview of Causation Factors

The coding system of contributory factors in OTS shows that 88% of LHD HGV drivers have at least one contributory factor attributed to them compared to 62% of RHD HGV drivers. The figures are lower in the national data but show a similar difference. One of the reasons for the difference is likely to be due to the availability of the 'inexperience of driving on the left' factor to investigators.

Although the 2005 contributory factors system is fundamentally the same in both datasets the OTS project benefits from experienced investigators who study hundreds of accidents per year, and the inclusion of damage only accidents. It is interesting though, with the large national dataset, to look at factors in HGV accidents and examine if trends are similar to the OTS data set. The contributory factor which features the most in the national data for HGVs is 'failed to look properly' with 48% of LHD HGV drivers and 36% of RHD HGV drivers (who had at least one factor attributed to them) being attributed with this factor. Other interesting factors for the LHD foreign registered HGVs in the national data include; 'vehicle blind spot' and 'inexperience of driving on the left' with 36% and 14% of the sample respectively compared to only 7% and less than 1% for RHD HGVs. In the OTS LHD HGV sample, 76% of the HGVs are deemed to have 'vehicle blind spot' as a contributory factor where this was only recorded in 7% of RHD HGV accidents. The second most frequent is 'failed to look properly' with 72% and 31% for LHD and RHD HGVs respectively. 'Inexperience of driving on the left' features for 35% of LHD HGV drivers and understandably doesn't feature in the OTS RHD HGV sample.

Part of the large difference for the factor 'vehicle blind spot' between the two groups of HGVs could possibly be due to preconceived thoughts by investigators that a LHD HGV would suffer from a blind spot whereas a RHD HGV wouldn't suffer from this problem. It is a large difference though, and the authors believe it is indeed a significant issue for LHD HGVs when on UK roads due to the road network and driving style.

In the OTS sample LHD HGV drivers are 2.5 times more likely to be coded as performing a 'poor turn or manoeuvre' compared to RHD HGV drivers and 2.4 times more likely to be deemed to have 'failed to look properly'. It is clear that for LHD HGV drivers the factors 'vehicle blind spot' and 'failed to look properly' will be closely associated.

Further Work on Causation Codes in OTS

A large proportion of LHD HGV accidents involve contributory factors which are part of the driver action or experience categories whereas RHD HGV accidents also include injudicious action and road environment factors.

The national data shows that 'fatigue' is coded for 3.1% of RHD HGV drivers compared to only 2.4% of LHD HGV drivers. This figure differs to the results in OTS where 6.5% of RHD HGV drivers are attributed with this factor and 'fatigue' doesn't feature in the LHD HGV sample at all. A possible reason for this is due to the level of severity of the LHD HGV accidents, mainly being slight injury or non-injury, so tachograph interrogation could not be justified (OTS investigators are not allowed to request tachograph data from drivers) to establish driver hours. Further data from new investigation methodologies, translated driver interviews and specific questionnaires, will help inform the investigation of fatigue in the future.

The literature review highlights a VOSA report (2007) showing that half of foreign HGVs checked in 2006 had serious vehicle defects. In the national data it was observed that less than 0.5% of LHD foreign registered HGVs are coded as having a vehicle defect as a contributory factor. Across the 6 factors analysed, vehicle defects are more of an issue for other HGVs, with 3.5% found to have been 'overloaded or poorly loaded' compared to only 0.1% of LHD HGVs. The small amount reported for LHD HGVs may be as a result of load checking at points of entry or exit to and from the UK, for safety on ferries or in the Channel Tunnel. In the OTS analysis no vehicle defect contributory factors are attributed to LHD HGVs at all. The most common vehicle defect factor for RHD HGVs is 'overloaded or poorly loaded' but only 8 out of 250 are attributed with this factor.

The findings in this paper of low instances of vehicle maintenance being a contributory factor concur with the ETAC study which reports that the scope for reducing accidents and injuries through measures aimed at vehicle maintenance standards may be limited. Also a study from Cooper et al (2006)[15] concludes that the important element with respect to imported vehicles (in their study) is driver performance, rather than vehicle safety. Additionally, it must be noted that OTS (and national) data do not result from full, specialist vehicle examinations as carried out by VOSA.

OTS Human Interaction Codes

The OTS human interactions system looks specifically at the driver's actions and influences. Firstly it is observed that generally for LHD drivers the interaction codes 'looked but did not see due to vehicle geometry'(80%) and 'intentionally entered into path' (39%) are the most frequent, followed by 'adopted a conflicting path' (20%). This further shows that LHD HGVs not only have an issue with the vision surrounding the vehicle, and as a result are encroaching on other road user's space, they are struggling on reading the road environment and road infrastructure.

The RHD HGV drivers in the OTS sample have a broad spectrum of interaction codes with 'inattentive', 'failing to avoid' and 'losing control' being the three most frequent. Generally the RHD HGV driver interaction codes cover the perception, conflict, attention and loss of control categories, suggesting that there is more of a driver error and distraction problem compared to the perception and judgement issues attributed to LHD HGV drivers.

The literature review reports how mental load on a foreign driver can be high due to unfamiliar road layout and road user behaviour, along with dealing with a vehicle designed for the other side of the road. Specific examples are the difference in imperial and metric road signs, signs and instructions that are not given in the driver's native language and having different speed limits for HGVs compared to the posted speed limit. Mental load is very hard to judge in itself when investigating on-scene through OTS investigations, given the difficulty in discerning if drivers 'failed to look' due to mental load and/or vehicle geometry issues. These issues can usefully be the subject of further work using driving simulators and naturalistic driving experiments in controlled road environments. It should be noted that the figures are also significant for RHD HGVs.

In combination with the points above, foreign drivers also have to combat learnt patterns of behaviour. An example of learnt behaviour is how pedestrians from the UK instinctively look right when starting to cross mainland European roads. Foreign HGV drivers can find themselves in a situation of tackling an unfamiliar road layout and also combating a learnt pattern of behaviour, instinctively looking the ‘wrong way’.

New Technologies and Legislation

Manufacturers and policy makers are attempting to address the number of HGV accidents through the consideration of new vehicle technologies and possible regulation or legislation to govern their introduction.

If new technologies such as lane assist and monitoring systems such as radar sensing become implemented and more common place there may be a reduction in side swipe and lane changing accidents. However these systems will still be reliant on the driver reacting in time and taking an appropriate avoiding action. This technology will not necessarily reduce confusion for the driver regarding a strange road environment or road network, and with mental loads already suggested as being high the driver interface with any new technology must be carefully considered.

Legislation requires all new HGVs built since 2003 to be fitted with blind spot mirrors. A recent European directive requires additional mirrors to be fitted to all commercial vehicles over 3.5 tonnes registered after 1st January 2000, and this must be completed by March 2009. However it is estimated that the European HGV fleet will only be fully replaced by 2022. This legislation should hopefully see a reduction in the number of accidents occurring, however it is not necessarily addressing the entire human side of this problem. If the mirrors are positioned incorrectly for the height and seat positioning of the driver they can be ineffective.

Navigation tasks, especially in a foreign country, also place a mental load on the driver which may be reduced as satellite navigation aids are updated to include full and accurate UK map data, including key information for HGV drivers such as roads that are and are not suitable for HGVs. As the number of information systems, in-cab monitors and camera systems increase, to aid reversing manoeuvres or to reduce frontal blind spots for HGVs, so might the mental demand and possible distraction levels on the driver. If such demands are high and the driver is in a foreign country where the road network is different the driver may still be involved in similar types of accidents as before the new technology or mirrors were fitted.

These areas of driver aids and new legislation can be monitored to see how the accident rate for HGVs fluctuates, and in depth on-scene projects such as OTS can continue to investigate the causation factors involved.

Challenges for Real World Investigation of Foreign HGV Accidents

Due to the nature of the OTS HGV accidents with a large proportion of them being non-injury accidents, information such as driver hours is often not recorded as this information can only be collected for accidents where the injury severity is killed or seriously injured (life threatening or life altering) as the information is then retrieved by the police investigation team. This leads to a possible under representation from on-scene data for both LHD and RHD HGVs of fatigue factors.

It is not practical for on-scene research teams to carry out a full vehicle inspection on such large vehicles in regards to road worthiness, due to time constraints on-scene. For this reason maintenance and overloading issues may be under represented in the OTS data analysis. Similarly this will be the case for the majority of STATS19 reported accidents, especially those involving more minor injuries.

Of course the language barrier is a general challenge in the investigation of these accidents and although interactive translation methods for on-scene interviews do go some way to relieving this difficulty, as developed and piloted in OTS, not being able to communicate straight away with all accident participants will always introduce an extra difficulty on-scene.

Possible Actions to Increase Awareness

In order to reduce the number of LHD HGV collisions occurring in the UK a number of strategies could be implemented to increase driver awareness.

Information for driving in the UK could be given out at ports (or during crossings) to aid driver awareness and driver experience on a systematic basis. This information could include the permitted speed limits for HGVs on UK roads, advice on vehicle blind spots and typical scenarios such as changing lanes to the right, guidelines and suggestions on driving hours and taking regular driver breaks and an imperial to metric conversion chart to aid with speed limits, distances and heights of low obstacles.

In addition, advice and further instruction could be given to UK drivers to make them more aware of foreign vehicles and more considerate of the potential difficulties for foreign drivers. A possible area where this could be done is by expanding rule 164 of the UK Highway Code (overtaking large vehicles).

CONCLUSIONS

- During 2006 in Great Britain there were 952 injury accidents which involved a foreign registered LHD HGV, 0.5% of the total reported injury accidents for 2006. Other HGVs were involved in 9,597 injury accidents.
- In-depth OTS data shows HGV accidents accounting for 9.6% of the 3,504 available accidents, with LHD HGVs forming 19% of the HGV sample. Of all the accidents on the OTS database, 1.8% involve a LHD HGV.
- Both the national and OTS datasets show that the majority of LHD HGV accidents occur on the main arterial routes (Motorways, A roads and Trunk roads), in a greater proportion than RHD HGV accidents.
- In the OTS sample the majority of LHD HGVs are involved in a collision which is an 'overtaking or lane change manoeuvre', this is 3.4 times higher than for RHD HGVs.
- LHD HGV accidents present unique challenges for on-scene investigators. The language barrier is a general challenge in the investigation of these accidents but also the in-depth investigation of vehicle and trailer maintenance and driver hours can be challenging, leading to a possible under representation of maintenance, overloading and driver fatigue issues, compared to the literature, in the accident datasets.
- A trend which is a significant feature throughout the LHD HGV accident data for each accident causation system is 'vehicle blind spot' and 'vehicle entering a lane conflicting with others or swerving'. Due to the geometry of the vehicles, the potential blind spots on the right of a LHD HGV are worse than that on the right of a RHD HGV, causing particular problems when changing lane from the left to the right.
- The contributory factor which features the most in the national data and very highly in the OTS data for HGV drivers is 'failed to look properly'. For LHD HGVs this factor is closely associated with vehicle blind spots.
- The OTS human interactions system shows that for LHD drivers the interaction codes 'looked but did not see due to vehicle geometry' and 'intentionally entered into path' are the most frequent interaction codes, followed by 'adopted a conflicting path'. The LHD HGV driver codes cover perception and judgement issues whilst RHD HGV driver interaction codes cover the perception, conflict, attention and loss of control categories.
- Mental load on a foreign driver can be high due to unfamiliar road layout and road user behaviour. In addition drivers must manage a vehicle designed for the other side of the road. Although new technologies may be designed to help the driver (such as lane assist) there is a need for further research to better understand the mental work load experienced by foreign drivers and any Human Machine Interface issues that may in fact increase distraction as more new technologies are introduced.

REFERENCES

1) "Left-Hand drive HGVs: Dangers and Solutions", RoSPA, Birmingham, April 2007.

2) John Fitch, (2007) "Final Report LHD Vehicles Blind Spot Version 1.3", VOSA Research & Development Team.

3) "Survey of foreign vehicle activity in GB – 2003" Department for Transport, London, UK, 2003.

4) "Instructions for the Completion of Road Accident Reports, STATS20", October 2004, Department for Transport, London, UK.

5) "Accident data collected between 1997 and 2004" Kent Police (2004).

6) "Key Figures on Europe. Statistical Pocket Book 2006", Office for Official Publications of the European Communities, Luxembourg.

7) "Fitting blind spot mirrors on existing trucks - A consultation paper", Inland transport services, Directorate General for Energy and Transport, DGTren E3, 12th April 2006.

8) European Truck Accident Causation Study (ETAC). European Commission, Brussels, 2008.

9) "Driver fatigue and road accidents. A literature review and position paper", RoSPA, February 2001, RoSPA, Birmingham, UK.

10) Yannis, Golias and Papadimitriou "Accident risk of foreign drivers in various road environments", Journal of Safety Research, volume 38, issue 4, 2007, pp 471- 480.

11) "Half of foreign lorries tested on Britain's roads found to be dangerous" www.timesonline.co.uk/tol/news/uk/article1701531.ece. (April 25th 2007).

12) Hill, J.R., Thomas, P. D., Smith, M. and Byard, N. "The methodology of on the spot accident investigations in the UK", ESV Conference, National Highway Traffic Safety Administration, 17th International Technical Conference on the Enhanced Safety of Vehicles, pp 1-10. Amsterdam, June 2001.

13) Hill J.R., Cuerden R.W. "Development and Implementation of the UK On the Spot Data

Collection Study - Phase 1", Department for Transport. November 2005.

14) "Road Casualties Great Britain: 2006 Annual Report", Published 27th September 2007 by Transport Statistics, DfT, UK.

15) Cooper, Meckle, Nasvadi, Wiggins. (May 2007) "The Safety of Right-Hand Drive Vehicles in British Columbia", Insurance Company of British Columbia Performance Analysis Services.

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The views expressed in this work belong to the authors and are not necessarily those of the UK Department for Transport, Highways Agency, TRL, Nottinghamshire Police or Thames Valley Police.

IMPLEMENTATION OF STABILITY CONTROL FOR TRACTOR-TRAILERS USING THE NATIONAL ADVANCED DRIVING SIMULATOR

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ABSTRACT

Truck manufacturers are introducing Roll Stability Control (RSC) and Electronic Stability Control (ESC) systems on heavy trucks including tractor-trailer type vehicles. These systems are designed to assist a driver to avoid rollovers, and in the case of ESC, yaw instability in tractor-trailers. This paper reports on the implementation of stability control systems on the National Advanced Driving Simulator (NADS) for studying their effectiveness in mitigating tractor-trailer directional loss of control and rollover instability. Five driving scenarios were modeled to closely correspond to severe real-world driving situations. These included exit ramps, decreasing radius curves, and avoidance maneuvers. These were modeled using dry pavement and a snow-covered road surface. The simulator model was validated with actual test track data. This research provides a means to obtain simulator test data on drivers behavior in a tractor-trailer equipped with RSC and ESC during severe driving maneuvers which is new in this field of study. This paper describes the implementation of stability control systems on the NADS and validation of the NADS stability control model by NHTSA. Also, a brief overview of the experimental procedures and the designed driving scenarios used in the NADS study are given. Results of the validation indicate that the simulator study should provide data similar to what would be expected in actual vehicles, but due to limitations in the current NADS truck model it may not be possible to make direct comparisons of speeds achieved in maneuvers with an actual truck on a test track.

INTRODUCTION

Heavy trucks (trucks with a gross vehicle weight greater than 10,000 pounds) have long been the dominant mode of freight transport in North America, carrying an estimated 62 percent ($534 billion) of the total value of freight in 2006 and accounting for most of the growth in the value of North American freight between 1996 and 2006 [1]. Accordingly, the trucking industry has experienced significant growth, with the number of registered heavy trucks increasing by 26 percent from 1995 to 2005, and the miles traveled by heavy trucks increasing by 25 percent over the same time period [2].

The unique characteristics of heavy trucks – their size, weight distribution, articulation, and varying types of freight carried – make them particularly susceptible to single-vehicle crashes due to rollover or directional loss of control, such as jackknife. In their analysis of fatal heavy truck crash statistics, Moonesinghe et al. [3] found that a posted speed limit of 55 mph or higher, poor road conditions due to weather, and road curvature significantly increase the chance for rollover and jackknife, yet there is a converse relationship between harmful events and the size and weight of the truck and trailer. Their analysis shows that the heavier the truck and cargo, the more prone the truck is to rollover, but that the increased weight serves as a deterrent for jackknife. On the other hand, the odds for jackknife increase with the increase in the length of the truck and trailer (from a single to a double or triple trailer), while the odds for rollover decrease.

The increased presence of heavy trucks on North American roadways, combined with a significant number of fatal, injury, and property-damage-only crashes and the unique characteristics of heavy trucks and heavy truck crashes, suggests that attention should be paid to developing countermeasures to crash-imminent situations for heavy trucks. Recent research documenting the substantial safety potential of electronic stability control (ESC) systems for passenger vehicles points to one such countermeasure. ESC is a technology designed to assist the driver in keeping the vehicle on the road during impending directional loss of control or rollover situations. These systems use sensors to detect when the motion of the vehicle differs from that indicated by the driver's inputs, and can control individual brake pressures at each wheel, as well as override authority over the engine throttle, and in the case of a heavy truck, the engine retarder in order to correct the vehicle's path prior to the onset of a rollover or loss of control [4].

NHTSA supported this simulator study primarily as an effort to increase the available data on driver behavior using stability control systems on heavy trucks and to stimulate academic research in the field of heavy truck safety. The findings of this study are currently under evaluation by NHTSA, and the results are being prepared in a report by the University of Iowa National Advanced Driving Simulator (NADS).

This paper describes the implementation of stability control on the NADS and validation of the NADS stability control model by NHTSA. Also a brief overview of the experimental procedures and the designed driving scenarios used in the NADS study are given.

Background Information Relating to Benefits of Passenger Vehicle ESC

Research examining ESC systems on passenger vehicles and light trucks suggests a dramatic reduction in the number and severity of certain crashes caused by loss of control, including rollover [5]. For example, Dang [6] attributes ESC with the reduction in fatal run-off-road crashes, such as rollover, for passenger cars (36 percent reduction) and light trucks and vans (70 percent reduction), and the decline in rollover involvements in fatal crashes of 70 percent in passenger cars and 88 percent in light trucks and vans. Fatal single-vehicle crashes not involving pedestrians, bicyclists, or animals also experienced a reduction of 36 percent in passenger cars and 63 percent in light vehicles and vans due to ESC. Farmer [7] places the risk reduction for single-vehicle crashes due to ESC higher, at 41 percent, with a reduction in fatal crash risk for single vehicles of 56 percent. According to his analysis, ESC is most effective in preventing multi-vehicle fatal collisions for cars when driving on wet roads or curves at any speed, whereas ESC in SUVs appears to be most effective in avoiding multiple-vehicle fatal crashes only on high-speed roads [7]. NHTSA estimates that for passenger vehicles, 5,000-9,000 crashes and 5,300-9,600 fatalities could be avoided if all vehicles were equipped with ESC [8].

The primary objective of the simulator study was to estimate the extent to which heavy trucks may benefit from ESC systems, in light of recent results for passenger vehicles and more limited research on large trucks. Because of the limited exposure of ESC-equipped trucks currently in the fleet, a simple analysis of crash data for heavy trucks does not lend itself to determining the impact of ESC. Moreover, track testing of ESC systems are limited to the speed at which the experiments can be run with the proper safety requirements. On the other hand, hardware-in-the-loop systems and simulator experiments can be run at any speed provided the simulation results are properly validated for the events of interest.

TYPES OF STABILITY CONTROL TESTED

The specific types of stability control systems simulated in this study were Roll Stability Control (RSC) and Electronic Stability Control (ESC). ESC contains both roll and yaw stability functionality and shall be referred to as Roll and Yaw Stability Control (RSC+YSC) throughout the remainder of this paper. Stability control systems were tested in the following combinations: Baseline ABS only (no stability control), RSC, and RSC+YSC. Stability control system type and driving scenario were the independent variables in this study. Stability control system type was a between-subject variable, while scenario type was a within-subject variable. Each participant experienced five driving scenarios in addition to a familiarization drive.

The study used the NADS heavy truck cab and vehicle dynamics model. A common 6x4 tractor configuration was selected for this test. The simulation included the tractor pulling a fully loaded 53-foot box semitrailer.

PARTICIPANT SELECTION

Sixty drivers with a Class A Commercial Drivers License (CDL-A) completed participation in this study. There were twenty participants assigned to each of the three conditions (baseline, RSC, RSC+YSC To participate in this study, drivers had to meet the following criteria: possession of a valid, unrestricted, Class A Commercial Drivers License (CDL-A), a minimum of 6 months experience after obtaining CDL-A, an average of at least 2000 miles per month over the last 6 months, be in good general health, between 22 and 55 years of age, and pass a visual exam testing for color-blindness

NADS

The study used a high-fidelity full motion simulator located at the National Advanced Driving Simulator (NADS) facility at The University of Iowa. The NADS was instrumented with a functioning 1999 Freightliner Century Class cab with an Eaton Fuller 9-speed transmission (Figure 1). The tractor-trailer modeled is a 1992 GMC truck manufactured by Volvo GM Heavy Truck, model WIA64T, and a 1992 Fruehauf trailer, model FB-19.5NF2-53. A validation of the truck and tractor model was published previously by NHTSA [9]. The cab was mounted inside the 24-foot NADS dome. Four hydraulic actuators attach to the cab, producing vibrations emulating road feel. The dome is mounted on a yaw ring that can rotate the dome about its vertical axis by 330 degrees in each direction. The X-Y assembly produces lateral and longitudinal accelerations by moving about a 64-foot by 64-foot bay. The motion system provides the driver with realistic motion cues that allow the driver to feel acceleration, braking, and steering, as well as experience extreme maneuvers generally associated with critical driving events. For each run, the truck tractor was simulated pulling a fully loaded 53-foot box semitrailer.

Figure 1. Freightliner tractor cab in the NADS dome.

DAILY OPERATIONAL READINESS TEST

The Daily Operational Readiness Test (DORT) was a check of the NADS system before testing in the simulator would begin. For this project, an additional DORT was performed before each day of testing in the main study specifically checking the operation of the RSC and RSC+YSC systems. This test was also performed any time there was a change of hardware from RSC+YSC to RSC (or vice versa) during a single day of testing. The same test that was used to validate the simulation (explained later in this paper) was performed on the NADS to check the operation of the RSC and RSC+YSC systems. The results of this DORT test needed to match the expected parameter outputs before a main study drive could begin. These parameters included: tractor and trailer brake pressures, longitudinal and lateral acceleration of the tractor, tractor roll angle, and system activation. If these parameters did not match, the problem was diagnosed and fixed before testing resumed. This ensured that the operational performance of the RSC and RSC+YSC systems were correct for each day of testing or when a system hardware change was made between runs. A more complete description of the validation procedure used and DORT is included in reference [10].

EXPERIMENTAL DESIGN

The experiment was a split plot (i.e., combination between and within subject design). The between-subjects independent variable was stability control condition. There were three configurations that were being tested, Baseline ABS only (no stability control), RSC, and RSC+YSC. There were 20 subjects per test condition for a total of 60 participants. The within-subject independent variable was Scenario Event.

Scenarios

Each participant completed an initial familiarization drive and then drove five experimental study drives. The study drives can be categorized into two distinct groups, rollover and loss of control. The first group was designed to induce the potential for a rollover. These drives were modeled as occurring on dry pavement with a coefficient of friction of 0.85. The rollover scenarios were:

Incursion Right Event – The roadway has a posted speed limit of 60 mph and the driver encounters a vehicle that pulls onto the roadway, necessitating the driver to go around the incurring vehicles by steering into the oncoming lane, where the driver encounters oncoming traffic that requires a lane change back to the original lane. Figure 2 illustrates the right incursion.

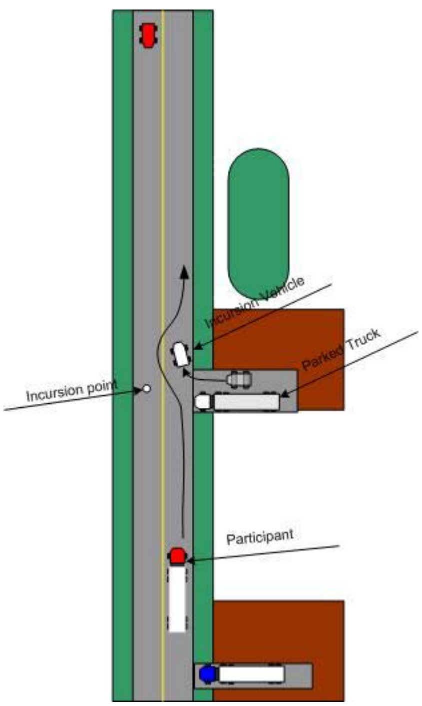

Figure 2. Incursion right event.

Decreasing Radius Curve – The driver encounters a decreasing radius curvature for which the driver is traveling at too great a speed. The posted speed limit of the decreasing radius portion of the curve is 35 mph. The curve has a road bank of 3 percent. Figure 3 illustrates the decreasing radius curve.

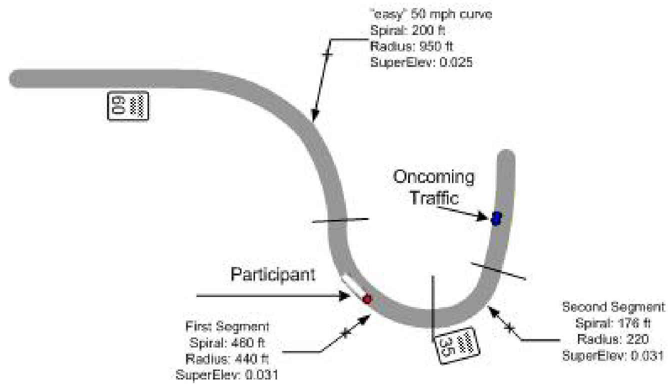

Figure 3. Decreasing radius curve.

Dry Exit Ramp – The driver enters an exit ramp too fast. The bank of the dry exit is 2 percent. The posted speed limit is 35 mph. Figure 4 illustrates the exit ramp.

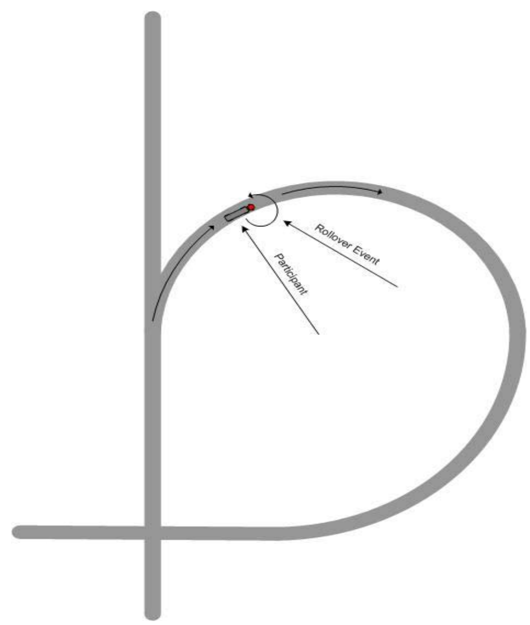

Figure 4. Exit ramp.

The remaining two drives were designed to induce the potential for a directional loss of control (e.g., jackknife). These drives were modeled as occurring on snow-covered pavement. The snow-covered pavement used modeled a surface with a coefficient of friction of 0.3. The loss of control scenarios were:

Incursion Left Event – On a roadway with a posted speed limit of 60 mph, the driver encounters a vehicle that pulls into the driver's lane, necessitating the driver to go around the incurring vehicles by steering onto the shoulder, requiring a countersteer. Figure 5 illustrates the incursion left event.

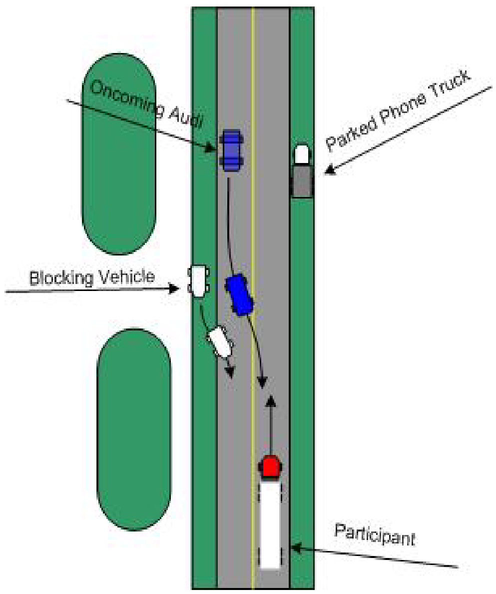

Figure 5. Incursion left event.

Snow Exit Ramp – The driver enters an exit ramp too fast. The snow exit ramp has a bank angle of 2 percent. The posted speed limit is 35 mph. The geometry is identical to the dry exit ramp (see Figure 4).

The familiarization drive, incursion right, decreasing radius curve, and dry exit ramps were completed on a dry pavement surface, whereas the incursion left and the snow exit ramp were completed on snow covered pavement.

NADS MODEL VALIDATION

The NADS truck model was compared with test track data from the NHTSA Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. The test maneuver used was a Ramp Steer Maneuver (RSM) with maximum steering angle at 190 deg with an angular rate of 177 deg/s. The steering angle was held constant for 5 seconds after reaching 190 deg.

The RSM was run for the baseline (ABS only), RSC, and RSC+YSC test conditions. Exact matching of values from test track data was not possible, as the NADS model was developed to simulate the braking properties of a Freightliner tractor and the inertial properties of a Volvo tractor. Also, the NADS truck was modeled with a rigid body trailer model and no torsional stiffness at the fifth wheel. All test track data were taken from VRTC tests of a Freightliner with Meritor WABCO stability control systems using a steering controller. Conversely, the NADS RSM runs had manual input of steering wheel angle. There were also slight differences in the actual test track surface coefficient of friction and that of the model. Because of these differences, data trends were compared and relative system performance was considered rather than matching exact parameter values.

Table 1 shows that the NADS and experimental Baseline threshold speeds were within one mph of each other. With RSC and with RSC+YSC both the NADS vehicle and experimental vehicle threshold speeds increased, in the range of 5 to 8 mph beyond the Baseline threshold speeds. For the experimental test vehicle, the RSC system provided a slightly greater margin of speed increase than the RSC+YSC system. On the test track, the RSC algorithm applied the brakes with more initial brake pressure than did the RSC+YSC thereby allowing a higher speed in the RSM than for the RSC+YSC runs. For the simulated NADS vehicle, the RSC+YSC and RSC threshold speeds were found to be within one mph of each other. These results indicated that the NADS RSC and RSC+YSC simulations did not exactly match but provided speed results that were close in magnitude to the actual vehicle.

Results from the simulator experiment should provide speed magnitudes that would be expected in

Table 1.
Rollover threshold speeds for RSM validation test

Rollover Speed (mph)	NADS	VRTC
RSC+YSC	33	32
RSC	32	35
Baseline	26	27

actual vehicles, but not in absolute terms. Therefore, direct comparisons to speeds achieved with an actual truck may not be possible with this model.

Comparison of Example RSM Runs

Figure 6 shows representative NADS simulation results from RSC runs of the Baseline vehicle and RSC-equipped vehicle. The runs shown on Figure 6 are the highest speed RSM runs conducted that did not result in vehicle rollover. The initial speed for the NADS Baseline run is 26 mph and for the RSC run it is 32 mph. Representative experimental results from the highest speed RSM runs conducted that did not result in vehicle tip-up onto the safety outriggers are shown on Figure 7. The initial speed for the experimental Baseline run is 27 mph and for the RSC run it is 35 mph.

The speed, lateral acceleration, yaw rate, and longitudinal deceleration of the NADS results (Figure 6) followed similar trends observed with the experimental data shown in Figure 7. The comparison shows similar decreases in lateral acceleration and yaw rate, and significant longitudinal deceleration due to the RSC brake activation. The RSC braking action slowed the vehicle and reduced the sustained lateral acceleration to a level that did not result in vehicle rollover. The activation of RSC was clearly demonstrated by the fact that the vehicle can be driven through the RSM without rollover at an initial higher speed than the Baseline vehicle without RSC.

Figures 8 and 9 show the brake line pressures for the NADS and experimental results respectively. In the figures, the left side brake pressures are shown in the left column and the right side pressures in the right column. Pressures 3-6 are the tractor drive axle brakes pressures and pressures 7-10 are the trailer brake pressures. There was no braking activity for the Baseline runs. With RSC, the NADS and experimental RSM runs showed similar trends in brake line pressures. For both the NADS and the experimental runs, the right side drive axle brake pressures nearly achieved their maximum of 100 psi for a sustained period of time. In addition to reducing the vehicle speed, this braking action resulted in reducing the yaw rate during these left turn RSM runs.

The Meritor WABCO RSC system was not designed to activate the tractor front axle (steer axle) brakes, and no brake line pressures were developed during the experimental RSM runs. However, the NADS did exhibit a slight amount of residual pressure up to 20 psi (137.9 kPa) on the steer axle brake lines during RSC activation. This amount of brake pressure was much smaller than what was applied on the tractor drive axles and trailer axles, and would only slightly affect RSC simulation results. However, resolving this issue would improve the overall accuracy and quality of the stability control hardware-in-the-loop implementation in the simulation.

LIMITATIONS OF SIMULATION

Every simulation model has limitations, and it is important to understand where those limitations may have been encountered in the study. There are two potential limitations related to the NADS vehicle dynamics and its interaction with the stability systems. The first is a known limitation, while the second is a potential limitation.

First, the fidelity of the NADS heavy truck model is limited by the rigid formulation of the model components. The major limitations of the current model are the lack of torsional stiffness in the fifth wheel and the lack of frame flexibility in the tractor. This resulted in the tractor roll response being equal to that of the simulated trailer. The tractor-trailer model is still valid for doing relative comparisons between the various study conditions. Another fundamental limitation is the use of table lookup data of tire forces measured in 1992. A full, functional tire model with recently tested tires would improve the fidelity and overall quality of the simulation results.

Second, the RSC and RSC+YSC systems are not simply "plug-and-play" devices, able to be installed in any tractor trailer interchangeably, although the RSC system requires much less tuning than the RSC+YSC, which must be configured with a variety of vehicle parameters. Indeed, it is necessary for a technician to configure the system to the truck by setting parameters related to the wheel size, wheelbase, etc. Every effort has been made to ensure that the hardware has been configured with the proper settings before delivery to the NADS. Additionally, the tractor-trailer model and its associated subsystems have been created with the highest fidelity possible within the constraints imposed by real-time simulation, and all the required signals have been supplied to the system's hardware-in-the-loop.

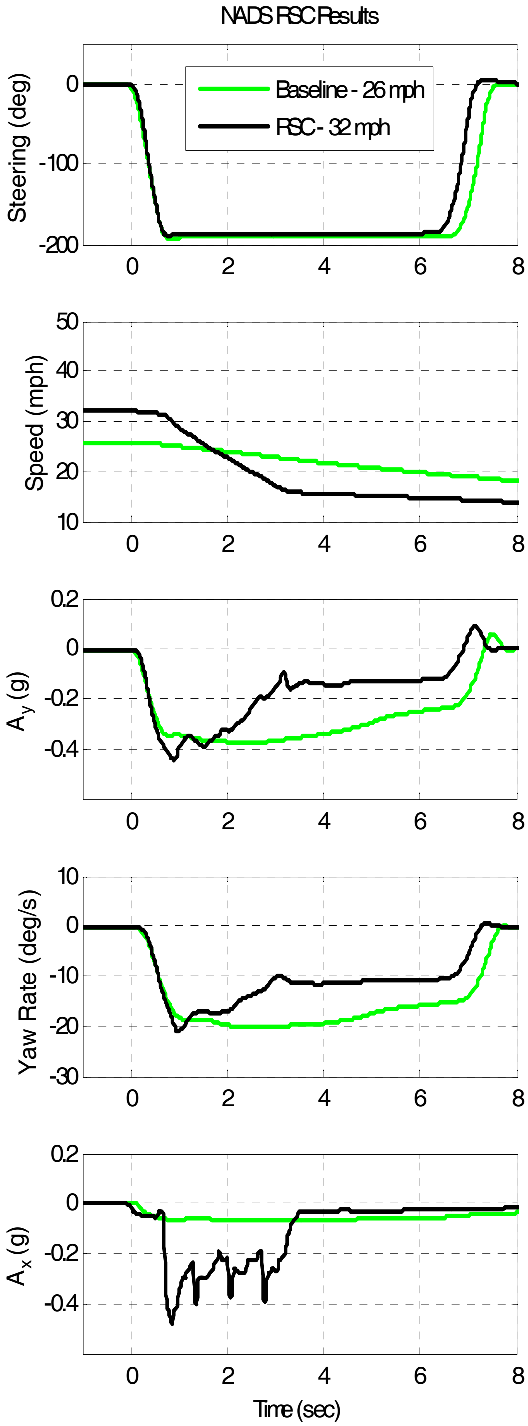

Figure 6. NADS RSC results.

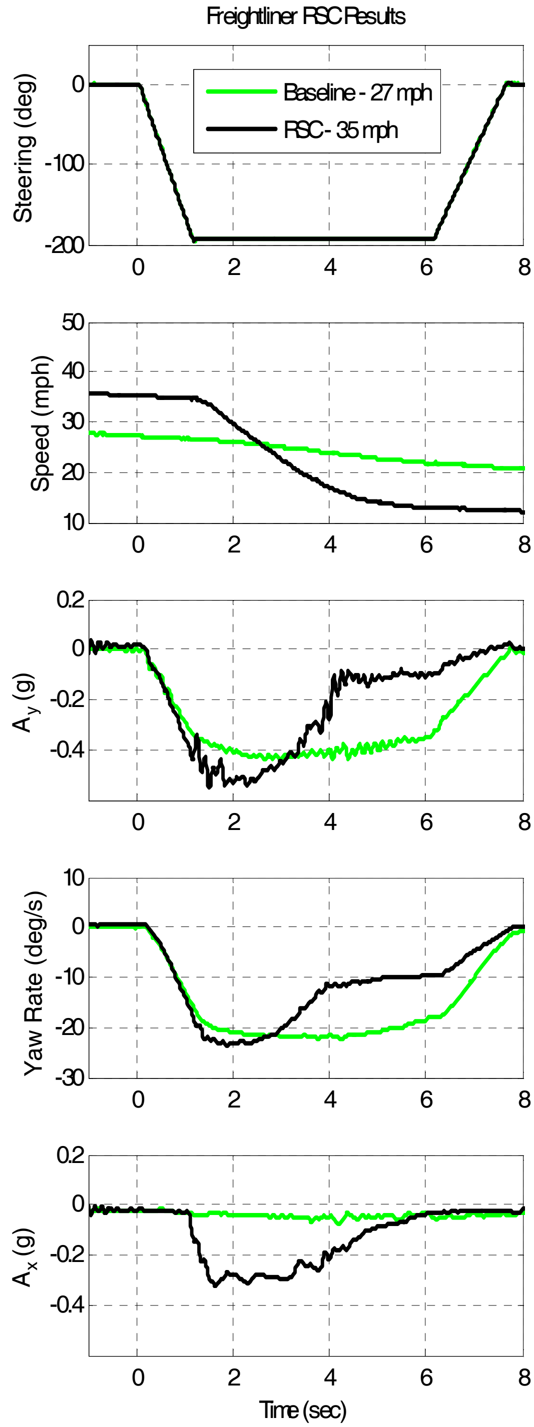

Figure 7. VRTC experimental RSC results.

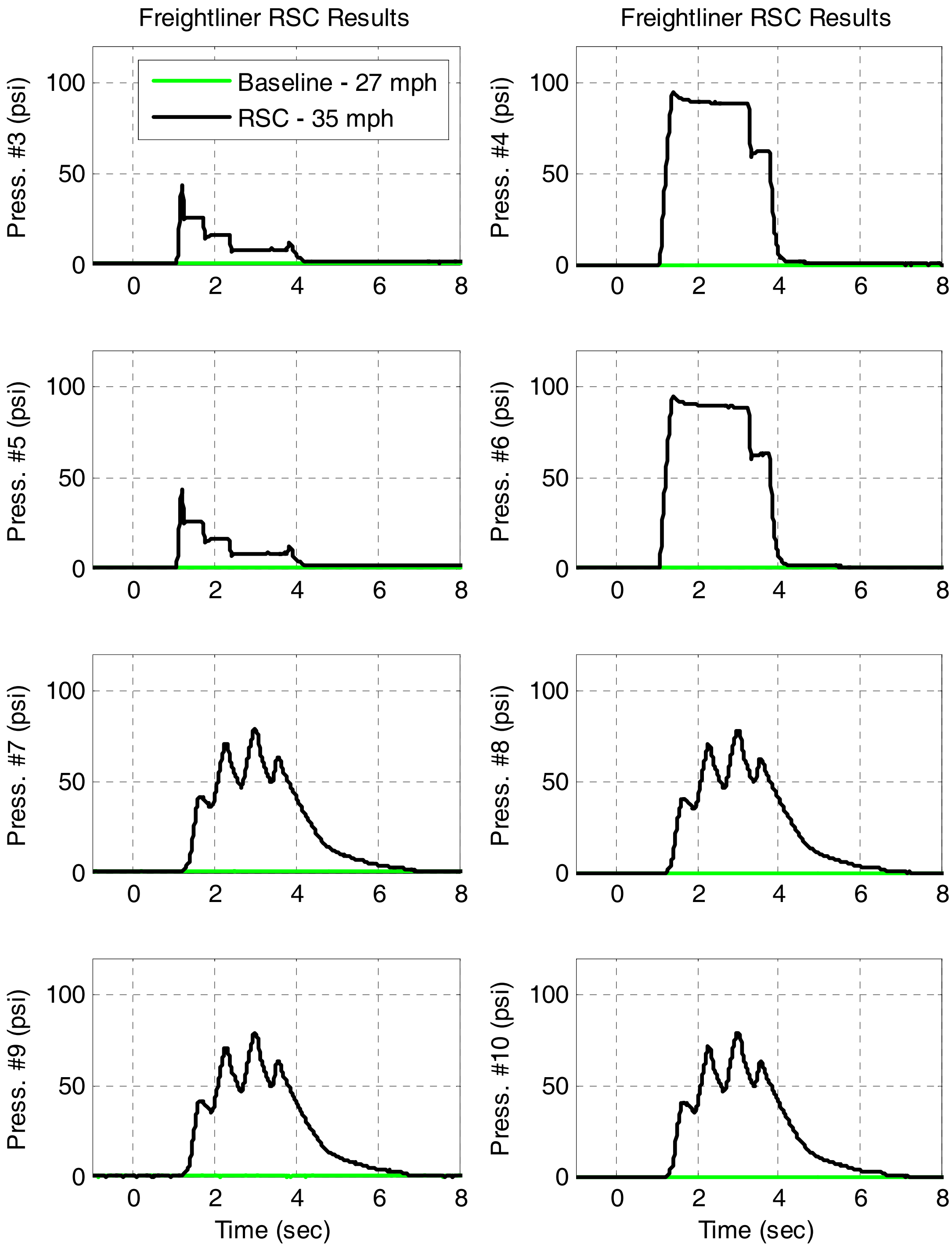

Figure 8. Experimental brake pressure lines – RSC.

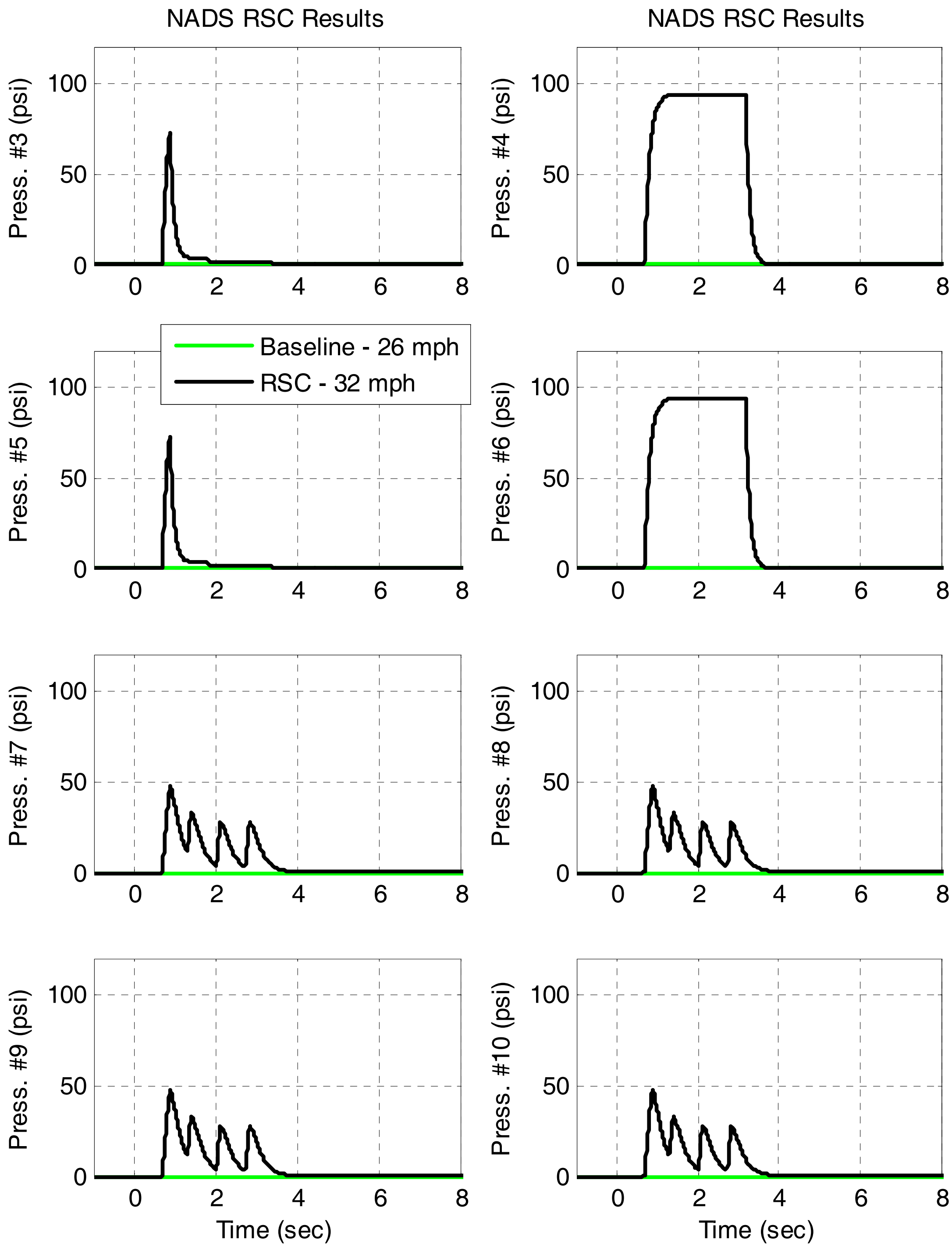

Figure 9. NADS brake pressure lines – RSC.

CONCLUSIONS

This paper presents NHTSA's effort into the implementation of electronic stability control systems for heavy trucks on the National Advanced Driving Simulator at the University of Iowa. The purpose of the study was primarily to increase the available data on driver behavior using stability control systems on heavy trucks, stimulate advanced academic research in this field, and to provide better means for understanding issues related to heavy truck safety.

A comparison of a RSM run on the NADS with actual test track experiments results in the following conclusions. First, speed at which rollover occurs in the RSM indicate that results from the simulator experiment provide similar results that would be expected in actual vehicles, but not in absolute terms. Second, direct comparisons to speeds achieved in maneuvers with an actual truck on a test track may not be possible with the current NADS model. And finally, further refinements to the NADS tractor-trailer model and the inclusion of a full, functional tire model with recently tested tires would improve the fidelity and quality of the overall simulation. The findings of the evaluation study on stability control for tractor-trailers are being prepared in a report by the NADS, University of Iowa.

REFERENCES

[1] Sprung, M.J. 2007. *Increased Trade Spurs Growth in North American Freight Transportation*. Research and Innovative Technology Administration, Bureau of Transportation Statistics. Accessed on 2/20/2008 at http://www.bts.gov/publications/bts_special_report/2007_05/html/entire.html.

[2] Federal Motor Carrier Safety Administration (FMCSA) 2007. *Large Truck Crash Facts 2005*. Analysis Division, February.

[3] Moonesinghe, R., Longthorne, A., Shankar, U., Singh, S., Subramanian, R., and Tessmer, J. 2003. *An Analysis of Fatal Large Truck Crashes*. National Center for Statistics and Analysis, National Highway Traffic Safety Administration. DOT HS 809 596.

[4] Federal Motor Vehicle Safety Standard (FMVSS) No. 126 Electronic Stability Control Systems, 49 CFR Part 571.

[5] National Highway Traffic Safety Administration (NHTSA). 2006. *Traffic Safety Facts 2005: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System*. National Center for Statistics and Analysis, DOT HS 810 631.

[6] Dang, Jennifer N. 2007. *Statistical Analysis of the Effectiveness of Electronic Stability Control (ESC) Systems – Final Report*. National Highway Traffic Safety Administration, National Center for Statistics and Analysis.

[7] Farmer, Charles M. 2006. Effects of electronic stability control: An update. *Traffic Injury Prevention* 7(4): 319-324.

[8] Final Regulatory Impact Analysis, FMVSS 126, Electronic Stability Control Systems, DOT Docket No. NHTSA-2007-27662.

[9] Salaani, M.K., Grygier, P.A., Heydinger, G.J. 2003. *Evaluation of Heavy Tractor-Trailer Model used in the National Advanced Driving Simulator*. SAE paper no. 2003-01-1324.

[10] Brown, T., Schwarz, C., Moeckli, J., Marshall, D., 2009. "Heavy Truck ESC Effectiveness Study Using NADS - Final Report," NHTSA, Washington, D.C., to be published.

COMMERCIAL VEHICLE SAFETY TECHNOLOGIES: APPLICATIONS FOR BRAKE PERFORMANCE MONITORING

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ABSTRACT

A brake system deficiency is the most common reason for a commercial motor vehicle (CMV) to be cited for a regulatory violation and to be taken out-of-service during a roadside inspection. As part of a major safety technology project intended to assess the state of the practice and potential contributions of advanced sensor systems, the Federal Motor Carrier Safety Administration (FMCSA) sponsored two studies on CMV brakes and related controls. The first study compared the performance of six types of brake systems and component sensors in a controlled, test-track environment under both nominal operating conditions and conditions where brake faults were deliberately introduced. The results indicated that all types of sensors tested (two different Hall-effect stroke sensors, anchor pins instrumented with strain gauges, embedded thermocouples, ABS wheel-speed sensors, linear potentiometers, and a pressure transducer) provided useful information on brake performance status. However, their accuracy and fault-detection properties varied considerably, influencing their potential use in operational settings. The second study assessed the performance and maintainability of brake monitoring devices in an urban transit fleet. Twelve test and 12 control transit buses were fitted with 3 brake performance monitoring (BPM) systems. The buses accumulated more than 1.2 million kilometers in aggregate, during a 12-month test period. In operational use, it was demonstrated that commercially available sensors can be used to improve the effectiveness and efficiency of brake performance system assessment and thereby reduce the risk of crashes attributable to poor brake performance. These studies provide new information directly comparing the performance of BPM systems in controlled and operational settings. Both study results are limited to the particular systems and applications tested. Study data are available from the FMCSA.

INTRODUCTION

Under Section 5117 of the Transportation Equity Act for the 21st Century of 1998, Congress required the U.S. Department of Transportation to "conduct research on the deployment of a system of advanced sensors and signal processors in trucks and tractor-trailers to determine axle and wheel alignment, monitor collision alarm, check tire pressure and tire balance conditions, measure and detect load distribution in the vehicle, and adjust automatic braking systems." A comprehensive technology scan, as well as numerous interviews with key industry stakeholders such as truck manufacturers, fleet operators, suppliers, and regulators, identified a variety of research areas. They included the design, functionality, and effectiveness of BPM systems for CMV applications.

Commercial vehicle braking system design and operation is directly linked to stopping distance and handling and, thus, to overall safety. Properly maintained and performing brakes are critical in preventing and mitigating crash situations. Although vehicle defects in large trucks are not commonly pinpointed as the causative factor in crashes, vehicle defects, when found, frequently involve malfunctioning or defective brakes.

For years, the CMV industry has been plagued by the significant number of trucks and buses operating on the highway with brake defects, despite attempts by many different groups to address the problem. CMV inspection data show that about 19 percent of all inspected vehicles (nearly one in five) have one or more brake defects. In June 2008, during a 72-hour intensive inspection initiative sponsored by the Commercial Vehicle Safety Alliance, 67,931 vehicles in Canada, Mexico, and the United States were inspected. Various vehicle-related defects and violations resulted in 23.9 percent of the vehicles examined being placed out-of-service and prohibited from operation until the defects were remedied. Slightly more than half of these out-of-service vehicles (52.6 percent) were cited for brake-related issues.

Optimally adjusted braking systems can help prevent or reduce the severity of CMV-involved crashes, even when the braking system is not the initial cause of the crash. Brake sensors, acting independently or as part of a coordinated system on a CMV, can measure dynamically and continuously the actual braking force at each wheel. Brake sensors can provide a warning to the driver, maintenance personnel, and roadside safety officials if the vehicle's braking ability is degraded to an unsafe level. In addition, brake sensors can provide information to aid in diagnosing the specific deficiencies. Brake sensors also can be integrated into a CMV's electronically controlled brake system in a "closed-loop" fashion to balance the braking action at each wheel. This will improve service life and provide additional input for controlling braking action at each wheel during crash avoidance maneuvers.

COMPARATIVE CONTROLLED TESTING OF BRAKE SENSORS

The first study documented the performance and operational characteristics of leading-edge technological approaches to monitoring CMV brake systems. It focused on comparing and contrasting the ability of the various sensors to detect abnormalities, defects, and maladjustments of the brake system. Multiple systems were installed on a tractor-trailer combination vehicle so they could be tested concurrently and under the same test conditions. A test matrix was developed to encompass a variety of controlled braking maneuvers, including low to high deceleration rates executed on dry and wet pavement, on level and graded surfaces, and with the CMV lightly laden and loaded to its gross vehicle weight rating (GVWR). All tests were performed on a test-track.

The study sought to answer questions concerning the performance of specific sensors and measures, including the following:

• Instrumented anchor pins for S-cam drum brakes — Does the output provide an accurate representation of braking forces? Is it necessary to instrument both upper and lower anchor pins? How responsive is the output? How could the sensors be used to detect defects? Is a simplified design possible?
• Wheel-speed sensing — Can antilock brake system (ABS) wheel-speed sensors be used to determine wheel slip? Can the relationship of wheel slip to brake force be used to detect brake system defects?
• Air chamber stroke sensing systems — How accurate and reliable are they? What defects can they detect? What malfunctions might they fail to detect? Is it important to monitor brake stroke continuously, or is measurement of over/under stroke sufficient?
• Deceleration measurements — Although comparing deceleration with air brake pressure input to determine total brake force can be used to detect brake defects, several important design issues remain unanswered. How accurate do the accelerometer and pressure transducers need to be? What is the allowable tolerance on input of the vehicle weight to produce reliable results? How does the system respond to normal brake wear? Does the system produce excessive false positives such that warnings might be ignored?
• On-board brake temperature measurement — Relatively low-cost thermocouples can readily be affixed to brake system components. How reliably and quickly could they detect brake system defects?

Baseline performance and sensor outputs were first established with all wheel/brake assemblies on the vehicle optimally adjusted and with no defects. The test vehicle, equipped with a new set of brake linings, was subject to Federal Motor Vehicle Safety Standard (FMVSS) 121 S6.1.8 (brake burnishing procedures). Braking performance of the vehicle was verified using a roller dynamometer performance-based brake tester (PBBT) to compare the brake force measurements from the various sensors to a reference standard.

The following sections describe the BPM systems and other instrumentation, the test vehicle, the test program, and the results.

Instrumentation

StrainSert Anchor Pin Strain Gauges. In 1998-1999, the National Highway Traffic Safety Administration funded a Small Business Innovative Research project to evaluate the use of strain-gauged pins to provide an indication of brake performance. A grant was awarded to StrainSert, West Conshohocken, Pennsylvania, which produces strain-gauged pins for various commercial measurement applications. For the evaluation, anchor pins were fitted with strain gauges capable of measuring the shear stresses applied to the anchor pins of the drum brake assemblies used on heavy-duty S-cam trucks and buses.

The StrainSert pins are designed to be interchangeable with conventional anchor pins and are held in place using a simple keeper plate. When the brakes are applied, the S-cam mechanism rotates, thereby opening the brake shoes in a clam-like fashion. As the S-cam end of the shoe opens, the other end rotates about the anchor pins. (See Figure 1 for a diagram of an S-cam brake assembly and Figure 2 for a photograph of the StrainSert anchor pins installation.) The primary shoe is always the shoe that immediately follows the S-cam mechanism in the direction of wheel travel. Real-world fleet experience has shown that the primary shoe typically experiences higher braking forces (and, therefore, more wear) than the secondary shoe. Likewise, the primary anchor pin should encounter higher forces.

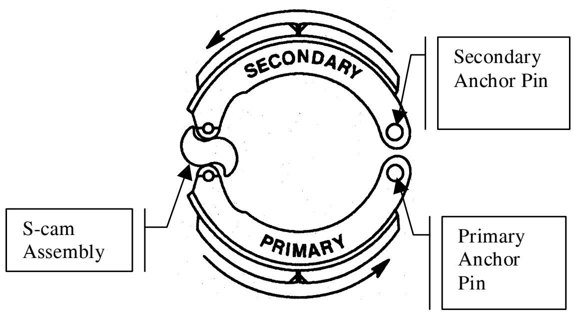

Figure 1. Left Intermediate Axle Brake Shoe.

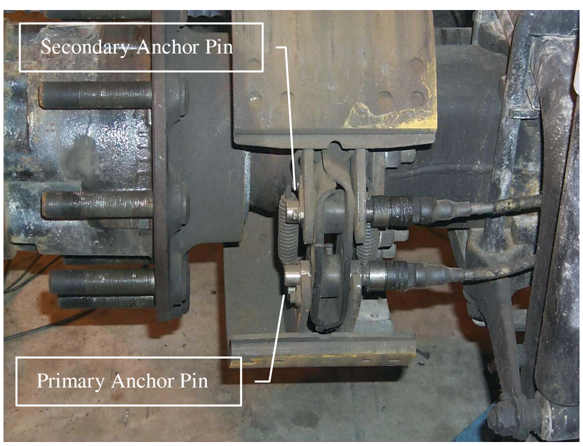

Figure 2. StrainSert Anchor Pins.

For the evaluation, each anchor pin was fitted with two strain gauges oriented 90 degrees apart, roughly in the "X" and "Y" direction. One of the strain gauges was mounted normal to the direction of rotation (the "Y" direction) and was intended predominantly to measure the mechanical non-friction, normal force exerted by the movement of the brake shoe as it moves against the drum. The "X" axis strain gauge was offset 90 degrees from normal and was intended primarily to measure the rotational friction force between the drum and the lining. The StrainSert anchor pins could be continuously monitored by measuring the electrical signal (voltage) generated by the strain gauges internal to the pins. A force-voltage curve was provided by StrainSert to translate the voltage signal output to an actual applied force measurement. StrainSert developed this force-voltage relationship in a laboratory setting by applying a known load on the pin and recording the output voltage.

<u>MGM E-Stroke</u>. MGM Brakes of Charlotte, North Carolina, the leading supplier of brake chambers (70 percent of the market), provided the study team with a commercial production electronic-stroke monitoring system or E-Stroke system. The E-Stroke system consists of a Hall-effect sensor and a magnet that strokes in parallel with the actuator piston rod to induce a voltage change. The E-Stroke system is illustrated in Figure 3. A communication module processes this voltage change and determines the status of the brake system. The communication module is capable of detecting normal stroke, over stroke, dragging brake, and a non-functioning brake actuator. The sensing hardware is contained within the air brake chamber, eliminating packaging interference with other components and protecting the hardware from the environment. Retrofitting a tractor with the E-Stroke system would require replacement of the standard brake chambers. Although the E-Stroke system is designed as a pre-trip inspection tool, the system continuously monitors the status of the brake system and can provide a visual indication of a stroke-related fault on a cab-mounted display.

Figure 3. MGM E-Stroke System.

<u>Spectra Products Brake Inspector</u>. Spectra Products, Inc., of Etobicoke, Ontario, provided Brake Inspector, another commercial production brake chamber stroke sensor system. This system, shown in Figure 4, is similar to the MGM system in function, using a single Hall-effect sensor, but the sensor hardware is mounted outside the brake chamber. Therefore, unlike the MGM E-Stroke system, the Spectra Brake Inspector can be retrofitted to existing tractors without complete replacement of the brake chambers. The signals from the sensors are routed to a display module mounted inside the cab. The Spectra Brake Inspector is also designed as a pre-trip brake status indicator, as well as a real-time brake-stroke status monitor. Spectra also includes a mechanical measurement indicator which is mounted on a clevis pin and provides a visual means to check the brakes in the event of a power or display failure.

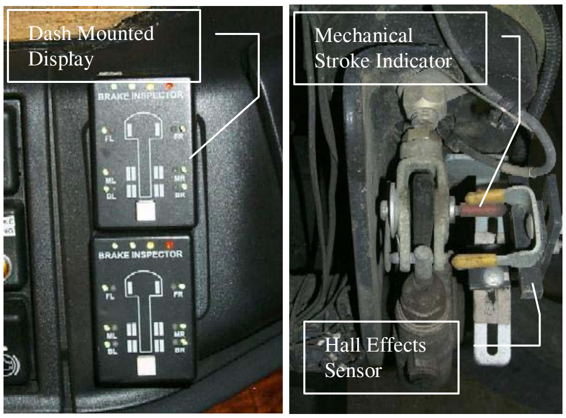

Figure 4. Spectra Brake Inspector.

__Thermocouples__. Standard Type J thermocouples were included in the instrumentation suite to determine whether they could be used reliably to detect brake defects, as well as to provide a temperature reference for evaluating the other sensors and systems. Temperature is an indication of brake adjustment status. Disconnected or backed-off brakes run cooler than properly adjusted brakes, while dragging brakes run hotter. The thermocouples were mounted at varying depths within the shoe lining to test their sensitivity in determining brake deficiencies.

__ABS Wheel-Speed Sensors.__ Wheel-speed sensors are a standard component of ABS systems used on heavy-duty trucks and buses. The variable-reluctance sensor is the most common type of wheel-speed sensor used in the industry. It uses a small internal magnet and coil of wire to generate a signal to the ABS control module. Each wheel and axle assembly is equipped with a gear-shaped tone wheel that rotates near the sensor. As the tone wheel rotates, a magnetic field fluctuates around the sensor and induces alternating current (AC) voltage in the internal coil windings. AC voltage is sent through a two-wire connector and harness to the ABS control module. The ABS controller interprets the AC voltage and frequency from the variable-reluctance sensor as a wheel-speed signal input.

ABS wheel-speed sensors can be used to measure individual wheel slip by comparing the calculated speed of each wheel against the calculated average for all wheels or against some other actual speed reference, such as a transmission signal or an optical fifth wheel that measures ground speed. This wheel-speed comparison capability is what enables the ABS, as well as traction-control functions. Further, it has been demonstrated under controlled conditions that the braking force at each wheel affects the rotational speed of that wheel compared with other wheels. If the braking force is low on a given wheel assembly, the wheel will tend to rotate a fraction faster than the other wheels. Conversely, if the braking force is high, the wheel will rotate slightly slower.

__Linear Potentiometers__. The linear potentiometers used in the evaluation (model number JP73213) were manufactured by Penny and Giles Controls, Ltd. These laboratory grade, special-purpose linear potentiometer sensors were mounted to the brake chamber push rods to measure their linear displacement during braking. Measurement of brake chamber stroke provides an indication of the driver's input to the air brake system. The potentiometers assisted in evaluating the limits of brake chamber stroke movement in detecting and determining brake defects. The potentiometers were also used to assist in evaluating the accuracy of commercial brake stroke sensor packages and as a reference signal for interpreting the performance of the other sensor systems.

__Pressure Transducer__. A low-cost pressure transducer from Texas Instruments (part number 84HP062T00150GSOC) was installed on the test vehicle to assist in evaluating the other sensor packages. Control pressure can provide an accurate measurement of the driver's input into the air brake system via the treadle valve and serves as a reference for various sensors under test. By knowing brake system input, the level of brake output could be better evaluated, permitting substandard brake performance to be identified.

Test Vehicle

The test vehicle was a new 2001 Volvo VNL 64T Series tractor, coupled to a tandem axle flatbed semi-trailer. The tractor came from a local truck leasing company with 823 miles on its odometer. This newer tractor was selected for the program to ensure the inclusion of ABS and to limit the potential for introducing unwanted variables caused by the use of older equipment. The flatbed semi-trailer design allowed easy loading and unloading with a forklift. Concrete blocks (4,300 pounds each) were chained to the deck of the semi-trailer in order to achieve an 80,000-pound maximum load. The vehicle accumulated 4,627 miles during the test program. Detailed specifications on the tractor, semi-trailer, and brake hardware are provided in Table 1, found at the end of this paper.

The test vehicle was equipped with the brake sensor packages and general-purpose sensors, which were installed per manufacturers' recommendations and instructions. The test vehicle was also equipped with a data acquisition system and other instrumentation, such as fifth-wheel sensors. After installation, all sensors were calibrated according to the manufacturers' instructions. Figure 5 shows the locations of the various sensors.

The test matrix included introducing pre-planned faults or defects on selected brake assemblies and repeating various braking maneuvers. Because the major objective of this test program was to evaluate the ability of the various sensor technologies to detect brake problems, 10 different brake deficiency scenarios were examined, ranging in severity from no deficiencies to 4 fully disconnected brakes. To maintain the stroke adjustment, the automatic adjustment feature of the slack adjuster was disabled on the affected brakes. Defects examined included various levels of out-of-adjustment brakes, disconnected brakes, and oil-soaked brakes. To simplify the analysis, no more than one deficiency was introduced to any given wheel or axle.

Data from the sensor packages were recorded using an onboard personal-computer-based data-logging system capable of recording digital, analog, and discrete sensor outputs. The system was also capable of simultaneously monitoring data (such as wheel-speed output) transmitted to the vehicle's SAE J1939 high-speed electronic network. The data was then processed off-board using conventional database and engineering plotting tools.

Test Program

The test program was designed to subject various types of brake performance sensors and systems to a comprehensive series of brake tests under a variety of operating conditions to evaluate their sensitivity and accuracy for detecting brake defects. These conditions included various initial braking speeds, deceleration rates, and surface conditions. The first phase of the testing focused on establishing the vehicle's (and sensors') baseline performance with properly adjusted brakes. Next, the brake defects were systematically introduced to determine the sensors' abilities to detect problems with respect to dry and wet road surfaces, empty and loaded conditions, low and high speeds, and low and high deceleration rates. This proved to be an effective approach since, for example, some sensors provided reliable detection of brake defects during hard braking but could not detect a problem during more routine brake maneuvers at lower deceleration rates.

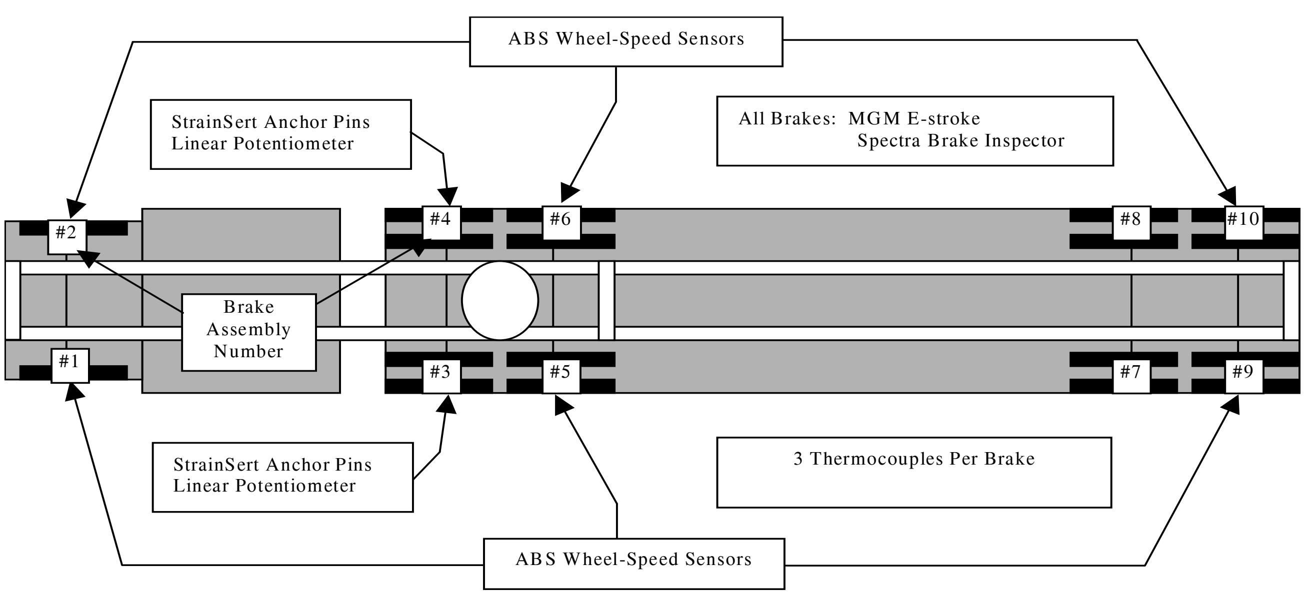

Figure 5. Sensor Locations.

In addition to the controlled deceleration tests, the brake sensor packages were subjected to simulated road tests to model the duty cycle that a vehicle would follow during extended mountain and city driving. These simulated tests were designed to evaluate the performance of the brake sensor packages when subjected to high brake temperatures and varying deceleration rates. For the simulated mountain test, the industry-recognized, Jennerstown mountain test procedure was administered on a flat, closed test track. The Jennerstown test procedure requires repeated brake snubs from 34 to 19 mph at a specified cycle time using a deceleration rate of 7.4 ft/sec/sec. The test begins with initial brake temperatures (IBTs) between 150° F and 200° F. In an effort to account for any degradation in baseline brake performance resulting from the testing itself and to provide a reference performance measurement, this procedure is repeated four times with cycle times of 125, 20, 70, and 40 seconds. The brakes were evaluated prior to the start (cold) by conducting a hard stop from 30 mph at a deceleration rate of 15 ft/sec/sec and again at the end of the test for the same speed and deceleration rate.

A PBBT was incorporated into the program to assist in evaluating the performance of the instrumented anchor pins against true service brake force. The PBBT used in this study was a roller chassis dynamometer-based system, capable of evaluating air brake systems on trucks and buses. PBBTs are commercially available and assist vehicle manufacturers and fleet operators by dynamically measuring the rolling resistance, brake threshold pressure, service brake force, parking brake force, and anti-lock braking systems (sensors, valves, and wiring).

Brake Burnish. The test vehicle, equipped with a new set of brake linings, was subject to FMVSS 121 S6.1.8 (brake burnishing procedures). These procedures required 500 brake snubs to be made from an initial speed of 40 mph and an exit speed of 20 mph at a deceleration rate of 10 ft/sec/sec. The brake snubs were performed at an interval of 1 mile. During this procedure, brake lining temperatures can reach 500° F or higher. During the 500-mile burnish, brake sensor packages and testing instrumentation were monitored and adjusted where necessary. Data was collected and used to determine that the sensors were working properly.

Data Collection Process. A Link data acquisition system (DAS) received information from 59 individual channels at a frequency of 50 hertz. Six of those channels were digital and were broadcast from the SAE J1939 network. A contact switch mounted to the brake treadle valve activated the DAS. Data were collected until the vehicle reached a complete stop. A memory cache built into the DAS recorded 1 second of data prior to the start of a braking event.

The actual data from each test run was stored in individual files on a Windows-based laptop computer that was mounted on the dashboard of the truck. The average braking event lasted about 3to 8seconds and generated approximately 17,000 data points (59 channels x 6 seconds x 50 data points per second). The data were downloaded to a compact disk at the completion of each day of testing. In total, the testing program generated approximately 375 megabytes of data.

The operator was responsible for manually recording the test identification number and other specific information, including environmental conditions, IBT, average control pressure, stopping distance, and the time required to stop the vehicle. The operator was also responsible for monitoring and documenting data generated from three sensor packages. These self-contained systems were not connected directly to the Link DAS, as they did not have signal output suitable for recording.

The data generated from the brake test program were imported into a Microsoft Access database specifically developed for this project. A graphing applet (Tee Chart Pro, Steema Software SL, Catalonia, Spain), capable of presenting multiple sensor outputs and scales on a single chart, was embedded into the database. This graphing capability was extremely useful in identifying trends in the data.

Results

Anchor Pin Strain Gauges. The track testing showed a highly predictable relationship between force data generated by instrumented (strain-gauged) anchor pins and the vehicle's deceleration rate. Instrumented anchor pins could accurately detect brake deficiencies in specific (individual) wheel assemblies, including out-of-adjustment, disconnected, and/or oil-soaked brake shoe linings. They also could measure the effect of an out-of-adjustment brake on the other (properly adjusted) brakes on a vehicle. Finally, as shown in Figure 6, data from instrumented anchor pins can be resolved into "X" (friction force) and "Y" (normal force) components and, thus, could point to causes for performance decrements. Notably, they could differentiate between an out-of-adjustment brake and a brake with oil-soaked brake shoe linings because an oil-soaked brake shoe lining generates less force in the "X" direction.

Figure 7 shows that primary anchor pin force was closely correlated with both the deceleration rate and the actual braking force (as measured by the PBBT) of the vehicle. This observation has important implications from a commercialization perspective since it would be necessary to instrument only a single anchor pin to accurately measure brake force.

Figure 8 shows that for properly adjusted brakes, as well as out-of-adjustment brakes, the Y direction forces were about 2,000 to 3,000 pounds less than the X direction strain gauge. This might be expected, since the relative rotational friction forces for a given applied braking pressure remain high with dry brakes. However, with oil-soaked brake shoe linings, the coefficient of friction was reduced and the rotation friction forces (X direction) decreased significantly, while the force in the Y direction (outward mechanical force) actually increased as the driver applied brake pressure in an attempt to maintain the desired deceleration rate. With oil-soaked brake shoe linings, the Y direction forces were actually much higher than the X direction forces. This information could indicate to the driver and maintenance staff that the detected defect in the brake assembly (and associated reduction in brake performance) was caused by an oil-soaked brake shoe lining as opposed to an out-of-adjustment condition.

Stroke Sensors. The accuracy of the readings from the sensor systems varied, depending on the load, deceleration rate, and type of brake deficiency. Both commercial systems tested (MGM E-Stroke and Spectra Products Brake Inspector) had the most difficulty detecting brake deficiencies with the trailer unloaded and at low deceleration rates. The manufacturers of both systems state that they are intended to detect overstroke conditions during hard braking. Additionally, stroke measurement obtained from the systems tested is likely not accurate enough to be suitable for use in brake balancing applications that might leverage the precise wheel-by-wheel braking control capability of electronically controlled braking systems. Unlike the instrumented anchor pins, brake stroke monitoring could not differentiate between out-of-adjustment brakes and oil-soaked brake shoe linings. This is illustrated in Figure 9. Oil-soaked brake shoe linings caused the linear potentiometers to record an overstroke condition.

Brake Shoe Thermocouples. Because of the unpredictable variations in initial brake temperature, the comparatively slow response time of thermocouples, and their inherent general inaccuracies, the ability of brake shoe thermocouples to detect and differentiate brake deficiencies during discrete braking events was found to be very limited. In general, the simulated mountain tests showed that brake lining thermocouples were effective at determining brake defects during extended braking maneuvers. Given enough time and heat build-up, clear patterns emerge with out-of-adjustment, disconnected, and oil-soaked brake shoe linings. It is likely that brake assembly temperature would need to be compared across axles in order to determine brake defects, as typical braking temperatures differ for front, intermediate, and rear tractor axles, depending on the load.

Wheel-Speed Sensors. Wheel-speed sensors were sufficiently accurate to detect grossly out-of-adjustment and disconnected brakes. However, they were not accurate enough to detect brakes that were 1/8-inch or less beyond the readjustment limit. Although they were able to detect performance decrements stemming from oil-soaked brake shoe linings, they were not able to differentiate between out-of-adjustment brakes and oil-soaked linings. Finally, wheel-speed data broadcast on the J1939 network was significantly less accurate than data from actual ABS wheel-speed sensors; but it was still able to detect grossly out-of-adjustment, disconnected, and poorly performing brakes. See Figure 10. The advantage of utilizing wheel speed as a means of diagnosing brake performance is that sensors are already on-board all CMVs equipped with ABS.

Figure 10 shows that the left front and right front relative wheel speeds were symmetric around zero because the average of the absolute left side and right side speeds was equal to the front axle speed. The relative speeds of the rear wheels differed from the front axle speed by as much as 1.6 mph during this braking maneuver. The low resolution of the relative wheel-speed data (0.04 mph) is illustrated by the abrupt transitions from one wheel speed to another in 0.04 mph increments. The transmission frequency of the J1939 wheel-speed message (100 milliseconds) is evident from the roughly 0.1-second steps in the data traces.

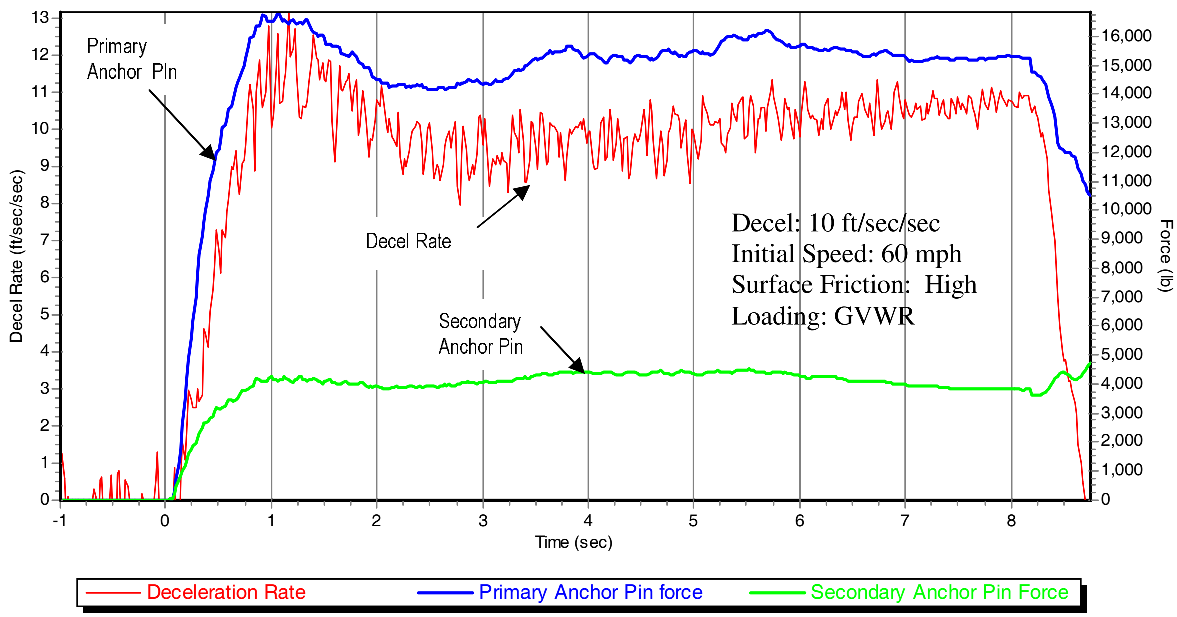

Figure 6. Primary and Secondary Anchor Pin Force During Moderate Deceleration.

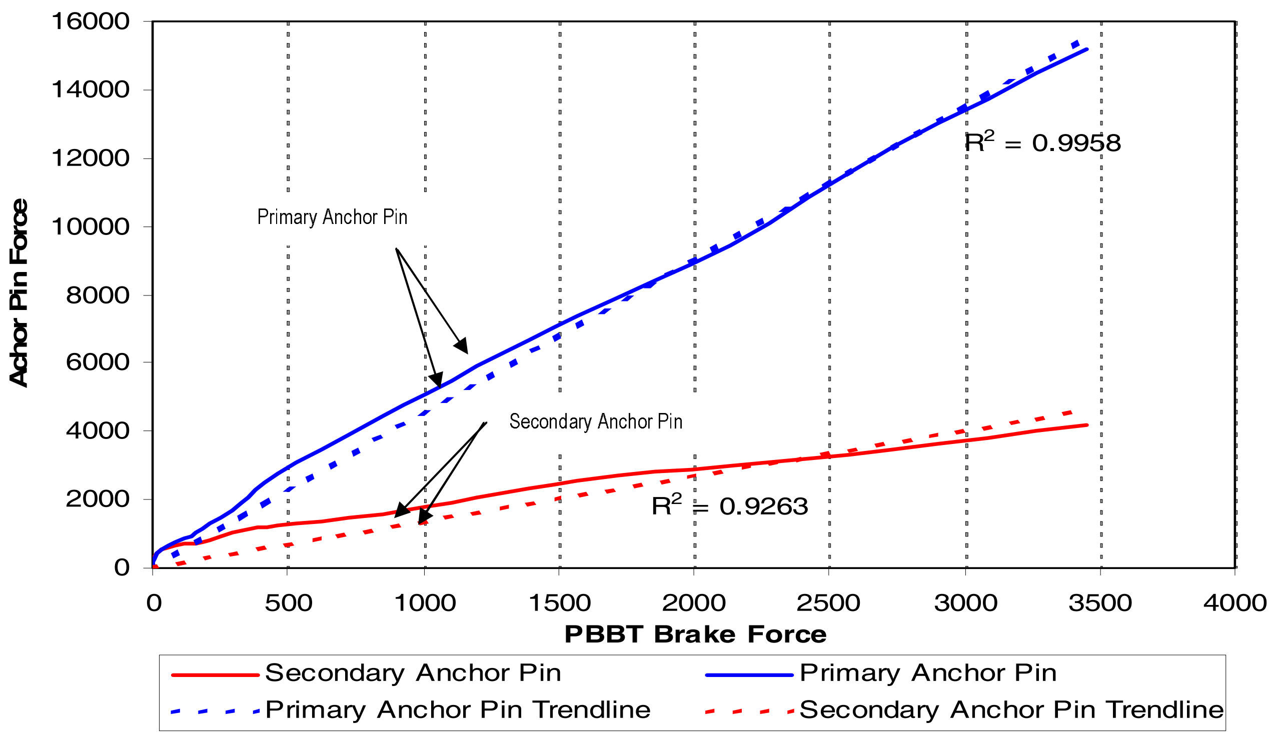

Figure 7. Anchor Pin Force vs. PBBT Brake Force.

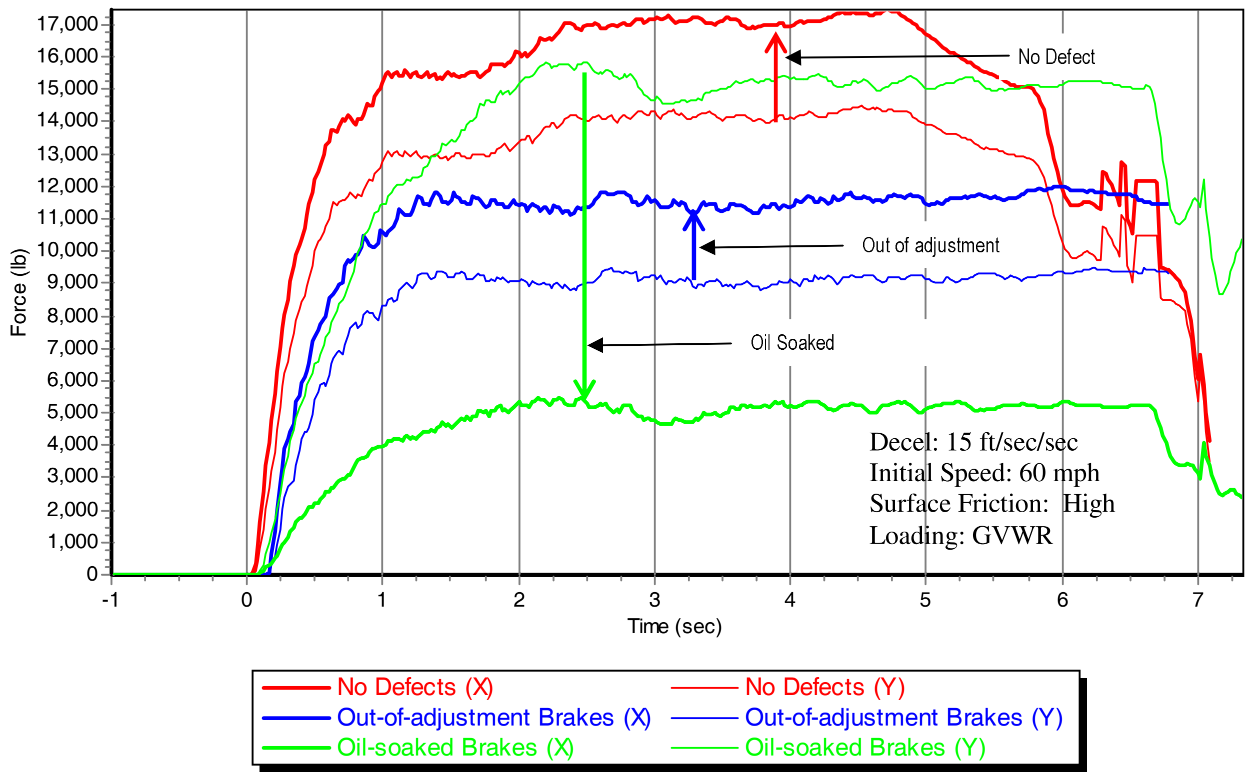

Figure 8. X and Y Anchor Pin Forces, Left Intermediate Brake Assembly, Under Various Defect Conditions.

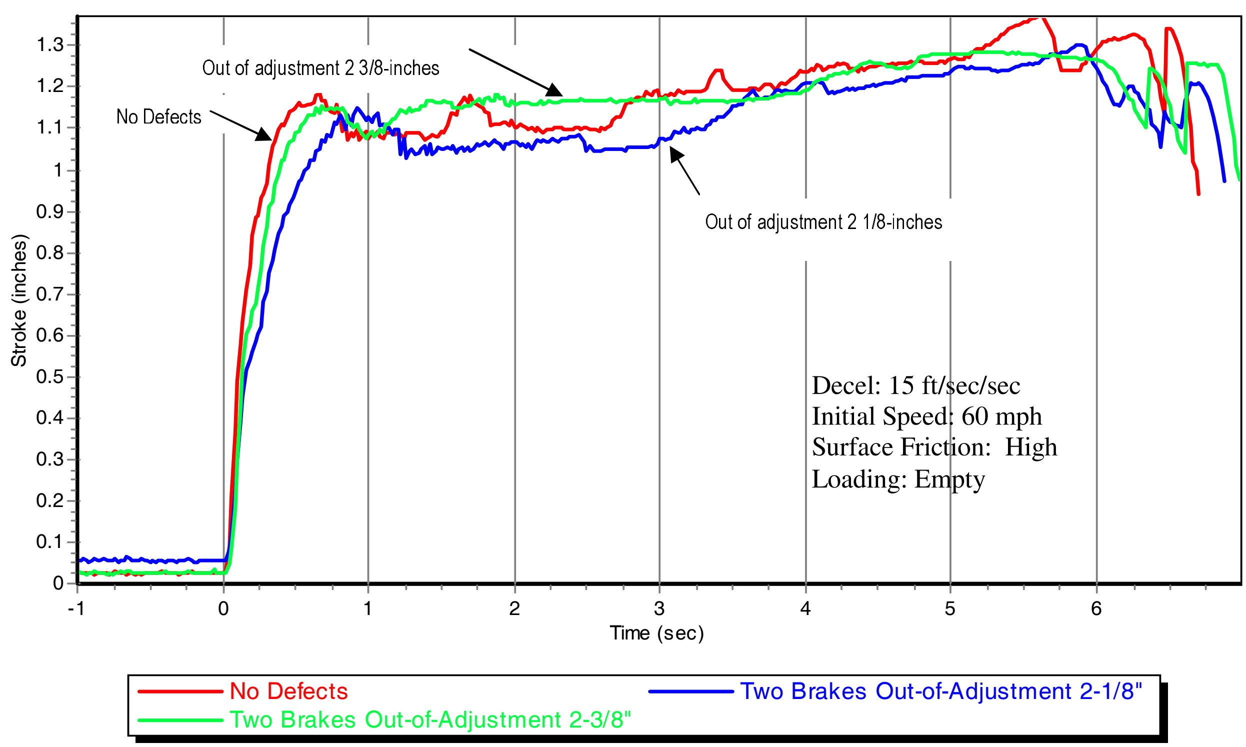

Figure 9. Brake Chamber Stroke Measured on Properly Adjusted Brake Assembly (Right-Intermediate) with Left Intermediate Brake Out-of-Adjustment.

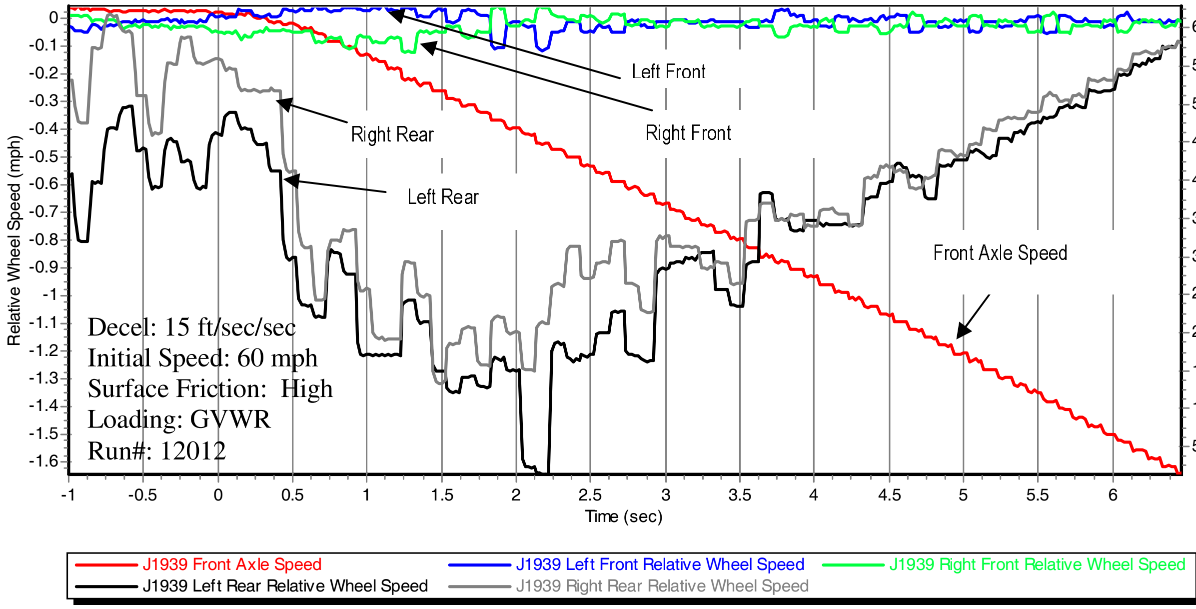

Figure 10. Wheel Speeds Relative to the Front Axle Speed with Properly-Adjusted Brakes.

BRAKE PERFORMANCE FIELD OPERATIONAL TEST

The second study focused upon documenting and evaluating several leading-edge BPM systems in a fleet setting. The study team sought to identify a commercial fleet operator (or host fleet) with characteristics that would allow for effective and fair evaluation of systems and technologies. These criteria included: an operating environment and duty cycle that could be considered severe for brake and tire wear; homogeneity of the fleet in terms of vehicle type, make, and model; consistency of operations within the fleet relative to driver assignments, routes, mileage accumulation, and maintenance operations; and a strong commitment by the host fleet to evaluating these systems in a controlled study for possible implementation in its own fleet.

The host fleet selected was the Washington Metropolitan Area Transit Authority (WMATA). WMATA operates approximately 1,500 buses in Washington, D.C. and the surrounding metropolitan area. Transit bus platforms were selected for this field test because their severe urban, stop/start duty cycle leads to accelerated brake and tire wear (thus challenging the sensor systems). In addition, the fundamental brake and tire designs are very similar to those on a conventional tractor, thus allowing the results of this study to be extended to heavy-duty (class 8) trucks.

The test fleet consisted of 12 Orion VII series, 2005 model year, urban transit buses. The buses are a “low floor” design, 40 feet long and 102 inches wide, and operate on compressed natural gas. Each bus’s GVWR is 42,540 pounds. The passenger capacity is 41 seated and 36 standing passengers for a total of 77 passengers. The curb weight of the buses is 30,990 pounds. The 16,500-pound front and 28,600-pound capacity rear axles are manufactured by Rockwell. Four S-cam Meritor brake assemblies are mounted on each wheel end. Front brakes measured 16-1/2 inches by 6 inches, and the rear brakes measure approximately 16-1/2 inches by 8-5/8 inches. Table 2 provides a full vehicle specification and can be found at the end of this paper.

The study team evaluated 3 BPM systems (as well as the 3 tire pressure monitoring systems) on 12 heavy-duty urban transit buses in revenue service for a period of one year. A control fleet of 12 identical buses was operated in a similar manner and used for comparison. A maintenance garage located in Arlington, Virginia was selected as the test site, based on the availability of buses of a consistent age and operating environment and on the experience and low turnover of the maintenance staff. With the assistance of WMATA and BPM system vendors, the study team retrofitted the candidate systems on the buses at the garage. The buses operated in an area covering approximately 300 square-miles south and west of Washington, D.C. The majority of miles were accumulated in an urban environment with minimal high-speed highway travel. The buses averaged 16 miles per hour in revenue service and were driven an average of 129 miles per day.

WMATA staff recorded all maintenance and fueling activities and entered the data into a maintenance management database. This information was made available to the study team for evaluation. At the conclusion of the test, maintenance staff were interviewed about their experience operating and maintaining the systems. Other than the standard data-recording capabilities of the candidate systems, no additional (or special-purpose) data-logging devices were added to the vehicles. The system status displays were located out of the drivers' view per the request of WMATA fleet managers. The study team and WMATA technicians were responsible for monitoring the systems' display status. This was done to limit driver distraction, as well as to reduce the incidence of operators halting a bus because of information from the displays. In the transit industry, it is common to limit the vehicle-related information available to the bus driver to basic items, such as vehicle speed, brake reservoir pressure, and dash-mounted warning lamps.

Three different BPM systems were evaluated under this program, as were three different tire pressure monitoring systems. The BPM systems selected (MGM E-Stroke, GeoDevelopment Brake Insight, and Strainsert) represented a range of technological approaches. The Strainsert and E-Stroke systems had been assessed in the controlled tests described earlier in this paper. The Brake Insight system uses a Hall-effect sensor mounted outside the brake chamber. The E-Stroke system was factory-installed on all of the buses but was the primary system under test in four buses. The Brake Insight and Strainsert systems were each installed on 4 buses, and 12 additional buses served as the study controls.

Project planning began in the autumn of 2005. Sensor system installation took place in the spring and summer of 2006, to accommodate the schedules of the fleet and the suppliers' field engineers. Data were collected for 12 months (November 2006 through November 2007). Over the course of the evaluation period, the systems were inspected weekly, and system data were downloaded as part of the test program. Additional data were collected in conjunction with WMATA's various maintenance inspections, which included a safety inspection every 3,000 miles and a comprehensive preventative maintenance inspection every 6,000 miles. In addition to the inspections, brake system performance was evaluated once per month using a roller-dynamometer PBBT.

The buses were placed on lifts for brake inspections, as shown in Figure 11. This enabled technicians to walk under the bus to inspect the brake lining thickness at each brake assembly and to measure brake pushrod stroke. The applied-stroke method was used. One technician would apply the brakes while at the driver's seat, and a second technician, outside the bus, would measure the brake stroke travel (in inches) and record it on the brake data collection form.

Figure 11. Test Bus on Platform Lift.

Results

• Onboard BPM systems were found to influence favorably WMATA's inspection practices. WMATA inspects buses every 3,000 and 6,000 miles. With over 200 buses operating out of a maintenance facility, these inspections require a significant amount of time. For the 3,000-mile inspection, WMATA has begun relying on the BPM systems to assess the brakes. This reduces inspection times and allows more buses to be inspected within a given period.
• The durability of BPM system sensors was excellent in a rigorous urban transit-operating environment. Only one sensor failure occurred during the 12-month test period. Maintenance actions on the sensors were few and were limited to broken wires, loose connectors, and sensor adjustments.
• In transit service, information from onboard monitoring systems needs to reach maintenance personnel in a timely fashion to be useful. WMATA's buses are equipped with a controller area network (CAN) databus and WiFi transmitter capable of wirelessly transmitting alarms from the bus to a server housed at the maintenance garage. Each time the bus returns to the garage, this data is off-loaded

and emailed to maintenance supervisors. The E-Stroke systems evaluated under this program were integrated into this CAN network. The study team found that buses with E-Stroke alarms were inspected and problems corrected in a timely fashion (on the same or the next day). On buses with monitoring systems that only communicated via in-vehicle display, a week or more could elapse before brake problems were addressed.

• MGM's E-Stroke system proved useful in the early detection of a manufacturing issue in the alignment between the brake chamber and slack adjuster on the test buses. The vehicle and brake manufacturers corrected this issue under the terms of their warranties.

• The WMATA technicians interviewed noted that the BPM system alerts provided them with useful information to quantify driver complaints and reduce their frequency. Complaints about brakes are time consuming to troubleshoot because they require performing an inspection on a lift. Technicians commented that the BPM systems reduced the number of driver complaints and provided real-time information they could use to decide whether the bus should be withheld from service.

• The BPM systems evaluated under this program were not able to detect worn brake linings in need of replacement. All but one of the test buses underwent a rear brake overhaul at roughly 70,000 to 80,000 miles into the field test. In the weeks and days leading up to the rear brake overhauls, none of the monitoring systems triggered an alarm indicating poor brake performance or excessive stroke travel. It should be noted that the Brake Insight system featured a wire-loop lining wear sensor embedded in the shoe lining. Unfortunately, the sensor embedded into the lining was placed at a depth lower than the minimum thickness used by WMATA to replace shoe linings.

• Onboard BPM systems provide a new source of information enabling technicians to identify and address brake issues. As with any new data source, a learning period is required to understand, interpret, and be confident with the data generated by these monitoring systems. WMATA experienced this learning process with the systems evaluated under this program. WMATA and the study team worked with BPM system vendors to tailor algorithms (and warning thresholds) for WMATA's transit vehicles to minimize false positives and improve the overall reliability of the information. Among the algorithms so modified were those relating to the base foundation brake setup, which was found to operate close to adjustment limits. The foundation brake setup coupled with the operating environment, which cycled the brakes frequently, caused hot brake conditions and resulted in overstroke alarms.

• Based on the results of the field study, as well as its previous independent testing, WMATA has confidence in BPM systems and plans to specify their use in all of the buses that WMATA purchases in the future.

CONCLUSIONS

Results from controlled track tests illustrated several key differences among the BPM systems. Commercial brake chamber stroke sensor packages can detect brake deficiencies and are very effective as a pre-trip brake inspection aid. Their "real-time" accuracy varies depending on the load, deceleration rate, and type of brake deficiency. The resolution and accuracy of stroke sensors is best suited for use in detecting brake maintenance needs and potential brake safety issues but is probably not appropriate for use in brake balancing systems. Instrumented anchor pins sensitivity, on the other hand, is such that they can also measure the effect of an out-of-adjustment brake on the other (properly adjusted) brakes on a vehicle. This capability lends itself for application to advanced brake balancing control schemes that might be possible with advanced braking systems. Finally, the resolution of wheel-speed sensors is sufficient to detect grossly out-of-adjustment and disconnected brakes. As these sensors are already included on new trucks as a component of ABS, they could be utilized to provide a low-cost approach to identifying brake adjustment problems.

In the brake performance field test, BPM systems provided information on the condition of the bus's brakes that was useful for improving maintenance practices and detecting brake abnormalities. This information had a significant impact on inspection practices and enhanced the overall efficiency of operations. While no firm procurement commitments were made, WMATA maintenance managers indicated at the end of the field study that they would consider the adoption of one or more monitoring technologies for new vehicle procurements and the retrofit of existing buses.

REFERENCES

Kreeb, R. M., B.T. Nicosia, D. Skorupski, and R. Radlinski, "On-Board Sensors for Determining Brake System Performance." Report FMCSA-PSV-04-001, December 2003.

Van Order, D., D. Skorupski, R. Stinebiser, and R. Kreeb, "Fleet Study of Brake Performance and Tire Pressure Sensors." Performed under Contract DTFH61-99-C-00025, Task Order 9, July 2005 – July 2008. Report forthcoming from FMCSA.

Table 1.
Track Test Vehicle Specifications

TRACTOR		TRAILER	
Tractor Model	Volvo VNL 64T	Trailer Model	Manac Flatbed
Serial Number	4V4NC9JH91N317953	Serial Number	2M512146311075573
Model Year	2001	Model Year	2001
Engine	Cummins	Suspension	Spring
Transmission	Meritor 10-speed	Length (feet)	48
Front Suspension	Spring	Wheelbase (inches)	477
Rear Suspension	Air	ABS	Wabco 2S2M
Wheelbase (inches)	214		
ABS	Wabco 4S4M		
GVWR (pounds)	50,350		

BRAKES			
	Front	**Intermediate /Rear Drive**	**Trailer**
Manufacturer	ArvinMeritor	ArvinMeritor	Semac
Type	S-Cam Drum	S-Cam Drum	S-Cam Drum
Size (inches)	15 x 4 Q-plus	16-1/2 x 7 Q-plus	16-1/2 x 7
Lining	R301FF	R301FF	CM18FF
Slack Adjusters	ArvinMeritor 5-1/2"	ArvinMeritor 5-1/2"	Haldex 5-1/2"
Chamber Type	MGM 20	MGM 3030	TSE 3030
Drum	Gunite 5890507	Webb 66864B	Webb 66864B

TIRES			
	Front	**Intermediate /Rear Drive**	**Trailer**
Manufacturer	Bridgestone	Bridgestone	Bridgestone
Make/Type	R227	M726	R196
Size	295/75R22.5	295/75R22.5	11R22.5
Pressure (psi)	110	110	105

WEIGHT DISTRIBUTION				
	Front Axle	**Drive Tandem**	**Trailer Axles**	**Total**
GAWR/GVWR	12,500	38,000	40,000	90,500
Loaded w/Trailer	11,950	33,640	34,030	79,620
Empty w/Trailer	11,410	13,280	8,920	33,610
Bobtail	11,210	8,350	N/A	19,560

Table 2.

Transit Bus Specification

TRANSIT BUS		
Bus Model	Orion VII	
Serial Number	4V4NC9JH91N317953	
Model Year	2005	
Engine	Cummins C8.3 Gas Plus	
Transmission	Voith D864.3E	
Front Suspension	Air	
Rear Suspension	Air	
Wheelbase (inches)	286 inches	
ABS	WABCO 4S4M	
GVWR (pounds)	42,560	
BRAKES		
	Front	**Rear**
Manufacturer	ArvinMeritor	ArvinMeritor
Type	S-Cam Drum	S-Cam Drum
Size (inches)	16.5 x 6	16.5 x 8.63
Lining	Meritor A3222F2296	Meritor A3222F2294
Slack Adjusters	Haldex, 5-Notch Adjustment	Haldex, 5-Notch Adjustment
Chamber Type	MGM E-Stroke Type 24 Long	MGM E-Stroke Type 30 Long
Drum	Dayton-Walther 85123561002	Webb 64051B
TIRES		
	Front	**Rear**
Manufacturer	Goodyear	Goodyear
Make/Type	City Tire	City Tire
Size	305/70 R22.5	305/70 R22.5
Pressure (psi)	115	115

WEIGHT DISTRIBUTION			
	Front Axle	**Rear Axle**	**Total**
Curb Weight, pounds	11,000	19,990	30,990
GVWR, pounds	14,780	27,760	42,540

HOW TO USE MIRRORS

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Paper Number 09-0469

ABSTRACT

Blind spots of trucks are a very often discussed problem. The usual way to reduce blind spots is to use a mirror. The new mirror regulation 2003/97/EC is improving the visible areas around a truck. The new trucks in Europe are equipped with mirrors which have to fulfil the new mirror regulation. This is the current technical situation. But how do the driver use these mirrors? What do they know about the new mirror systems? Do the driver know how to adjust the mirrors to provide the best view?

This paper will provide an overview about the mirror-related knowledge of German truck drivers and, subject to the type of mirror system mounted, how they are adjusted and used.

That is followed by the presentation of a solution to an old problem: so far there is no system which shows the driver of a truck whether his mirrors are adjusted in the right way or not. An idea coming from the Netherlands was to use markings painted on the ground to help the truck drivers to adjust their mirrors. This idea was improved by Daimler, MAN and DEKRA and is now offered e.g. to fleet operators to help their drivers.

Furthermore the remaining part is about how drivers use there mirrors on the road in different traffic situations.

INTRODUCTION

A driver has to take care of the traffic situation around the vehicle. This also includes the necessity to be able to see all relevant details. It is natural that a human is not able to see everything without turning around. This turning is necessary to get the required information. Is there another road user or an object? Do the other road user or the object lead to a possible conflict with the own vehicle? Only in case of visibility and noticeability the driver is able to act in a way to avoid a collision.

The simple driving manoeuvre of changing a lane is made by a passenger car driver by looking in the rear view mirror and turning his head to the side for a direct view. A truck driver on the contrary has with the same movement of the eyes and a large number of mirrors mounted to the cab still a large area he can not overlooked – the so called blind spot.

BASICS

Passenger cars do also have blind spots. They are primarily caused by the A-, B- and C-Pillars. The problem is limited to a 2-dimensional level and thus far smaller than that of trucks: A truck includes related to blind spots a third dimension. This is caused by the height difference between the eyes of the truck driver and the eyes of the other road users (e. g. pedestrians or car drivers, see Figure 1). The eyes of the truck driver are for most of the big European trucks (mass > 8.0t) roughly on a level of 2.5m, whereby the eye of a pedestrian will be on a level of 1.6m for a 50-percentile male. Besides the height of the drivers eyes there are two other main factors influencing the size of the blind spot. One is the height of the lower edge of the windscreen and the side windows. The other is the horizontal distance between the driver and the window. These three factors are influencing which points outside the truck will be visible. It is not unusual that a truck driver looking through the side window is not able to directly see a point on the ground in a distance of up to 7.5m beside the truck. For that area mirrors are required.

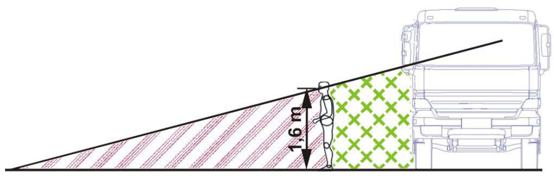

Figure 1. Visibility of a 50-percentile male from the position of the truck driver

The trucks (mass > 8.0t) which were following the former European mirror regulation (71/127/EWG [1]) were equipped with at least three mirrors on the co-driver's side and one on the driver's side. The new regulation 2003/97/EC [2] requires one additional mirror for the driver's side and one for the front. It is also allowed to use a camera monitor system instead of the front mirror. The new mirror systems have to show a larger area. Therefore a smaller radius of the mirror's convex surface is necessary. The currently allowed minimum radius is 300mm. It seems to be unbelievable, but with this radius the resolution limit of the human eyes is nearly reached. It is not possible to further reduce the radius.

The European regulation 2007/38/EG [3] requires the retrofitting of all trucks (N2+N3) first registered 2000 or later with the 300mm radius side mirror (only a few trucks are excepted).

Today we have the new mirror system at least for new trucks. What is the advantage of the new system? The truck driver is able to at least see an area of two meters in front of the truck and two meters on the co-driver's side. This is given by the requested areas of each single mirror. The problem is given by the fact that the truck drivers are not directly told how to adjust the mirrors in an optimal way. Many truck drivers are not taught about the differences between the old and the new mirror systems. Therefore they cannot use the advantages of the new mirrors. There was already a lack of knowledge for the old mirror system. Some truck drivers got their driving license when there was only one mirror on the right side. They were taught to adjust the mirror in a way that on the co-driver's side the rear axle should be visible in the mirror. This is not enough knowledge for today's mirrors.

CURRENT MIRROR USE

DEKRA initiated a study to look how the mirrors are adjusted on the road [5]. To have fast and comparable results the external point of the bottom edge of the wide angled mirror (class IV, see Figure 2) was measured. The results of the measured mirrors are separated to mirrors following the old regulation (71/127/EC) and the new regulation (2003/97/EC). The regulation 71/127/EC states that the interested point normally should be 3.0m behind the eyes of the driver and 2.5m beside the truck (co-driver's side). It was found that the wide-angled mirrors following the old regulation have a mean value which is very close to the target value (see Figure 3).

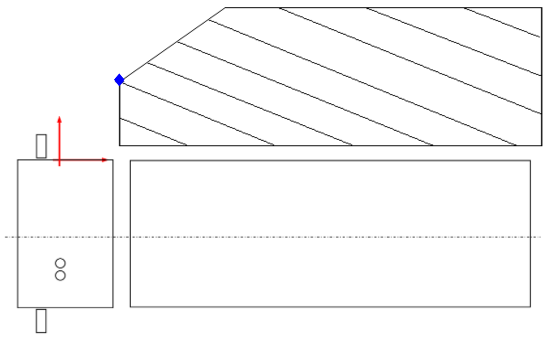

Figure 2. Explanation of measured point visible in the wide angled mirror (class IV)

The adjustment of the new wide angled mirrors do not have such a good result (see Figure 4). The target value should be 2.5m behind and 4.5m beside the truck. The mean value of the measured mirrors is 0.9 meter further away from the driver's eyes and 0.7 meter close to the truck. Both deviation reduce the visible areas and generate an additional blind spot which is not necessary. In consequence this means that in many cases the advantages of the new mirrors could not be used, because the mirrors only show more of the side of the truck and/or trailer.

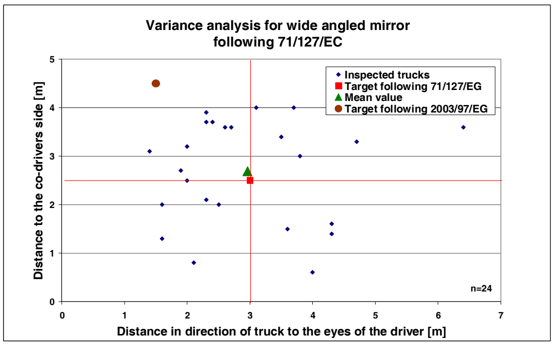

Figure 3. Variance analysis for wide angled mirrors (class IV) following the old regulation (71/127/EC) [5].

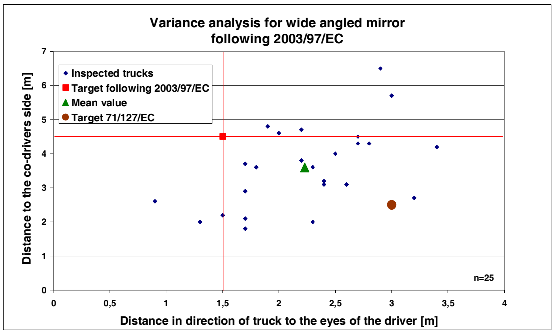

Figure 4. Variance analysis for wide angled mirrors (class IV) following the new regulation (2003/97/EC) [5].

The side mirror is one very important mirror for the blind spot problems of a truck driver. The other mirror which is often mentioned as a mirror to reduce the blind spot is the proximity mirror (class V). The origin intention of this mirror was to help the truck driver to drive as near as possible to a loading rack with a very low speed used for manoeuvring the truck. To make other road users visible is an add-on task for the proximity mirror. It is not easy for the driver to recognise another road user with this mirror while driving. The new front mirror (class VI), which was not part of the old mirror system, enables the truck driver to see an area of up to 2.0m in front of the truck.

MIRROR LIMITS

The driver has to look to the mirror to get information about possible obstacles which are not visible through the windows. When will the driver recognise those? Will it be enough to e.g. see a couple of hairs of a pedestrian? There are some problems in this context. It was already mentioned, that the proximity mirror was not given to the truck to see other road users. Figure 5 is showing what is visible from the driver's point of view for an old proximity mirror. Although the pedestrian is positioned in the area which is visible by the mirror, only left arm and left leg are shown in the mirror. Why? Only details which are inside the yellow pyramid on the picture could be shown by the mirror. The head, the main part of the body and the right leg are outside. Therefore these details can't be shown by the old class V mirror. Figure 6 shows the same situation for a new class V mirror. This mirror has a radius of 300mm instead of 400mm for the old class V mirror. Therefore this mirror is able to show the requested area given by 2003/97/EC. The pedestrian is not visible in total because of the same reason as mentioned for the old class V mirror. The bigger requested area is compressed to a surface which is nearly the same for old and new class V mirrors. Therefore every shown detail is smaller which requires a higher attention of the driver.

Not only the extent of an object shown by the mirror may be a possible problem. If the detail is shown near the border of the mirror there is a possibility to overlook this shown detail.
Figure 7 and Figure 8 are showing a cyclist positioned just above a point (marked by the stone) which is visible in the mirror. The recognizability is very limited. This example shows the difference between theoretical visibility and the real view. Additional in praxis the truck is moving e.g. in a turning manoeuvre and the driver has also to be aware of the vehicle which may be just front of the truck.

The blind spot problem does not only affect vulnerable road users. Figure 9 may indicate the impression, that everything is alright. Figure 10 is showing the reality outside the same truck. This was an original accident situation. The truck driver intended to change the lane to the right without seeing the passenger car. The car was hit in the area of the rear axle while it was driving in an urban area with roughly 50km/h. Caused by this first contact with the truck the car turned to the left. The car suffered a second collision with an oncoming motorcyclist. Coming back to the adjustment of the mirrors Figure 9 is directly showing the bad adjustment of the proximity mirror. Two third of the mirror is only showing the truck's door.

Figure 5. Visibility of a pedestrian by a old class V mirror (71/127/EC)

Figure 6. Visibility of a pedestrian by a new class V mirror (2003/97/EC)

Figure 7. Positioning of a cyclist just above a point in the corner of a class IV mirror (71/127/EG)

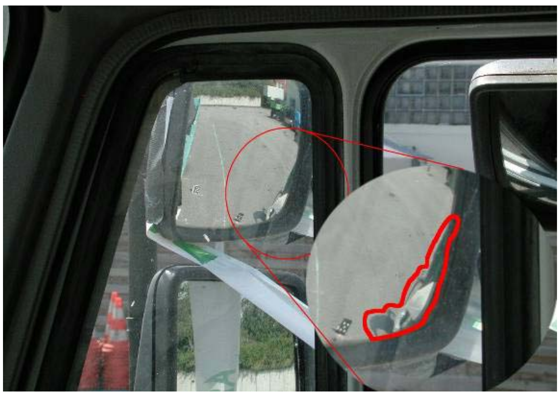

Figure 8. Visibility of a cyclist positioned just above a point in the corner of a class IV mirror (71/127/EG)

Figure 9. Example of driver view to the co-drivers side

Figure 10. Adjusted accident scenario with a visibility problem of the truck driver

MIRROR ADJUSTMENT

The main cause of the described accident were the not correctly adjusted mirrors. But how could these mirrors be adjusted in a better way? There is an idea coming from the Netherlands to paint special markings on the road (see Figure 11). These markings may give the truck driver an orientation to adjust the mirrors. The Dutch system has a small disadvantage. It requires much space beside the truck. Daimler, DEKRA and MAN found an improvement (see Figure 12). On one hand the new system requires less space to the side (4,5m instead of 15m). It includes on the other hand also markings for trucks with an old mirror system (yellow markings). There is also a separation between the mirrors at the co-driver's side and the front mirror. This is caused by the different points of orientation. The adjustment of the front mirror is orientated to the front of the truck whereby all other mirrors are orientated to the eye-point of the driver. There could be an extreme combination of truck and driver which may result in an adjustment of the mirrors with a small mistake. This mistake may end in a blind spot and cause an accident. Therefore Daimler, DEKRA and MAN decided to separate the system in two adjustment areas.

Figure 11. System to adjust truck mirrors following the regulation 2003/97/EC developed in the Netherlands

Figure 12. System to adjust truck mirrors following the regulation 2003/97/EC and 127/71/EC developed by Daimler, DEKRA and MAN.

The Dutch and the German system are only a help for the truck driver to have a point of orientation for the adjustment of the mirrors. The driver has the possibility to change the adjustment in the personally preferred way – the right adjustment stays the driver's responsibility.
There is another effect coming from this system. The system is leading to an increasing awareness of the problem. It was also used for public campaigns to show the people the blind spots of trucks. The more information other road users will get around this problem the more they could be aware of critical traffic situations.

This system is currently available in Germany at roughly 100 locations. Beside the locations of the three German developing partners there are additional supporting companies like another truck manufacturer, mineral oil companies, or truck hirer and forwarding companies. Some of these locations are also used by driving schools which teach new truck drivers. They start the driving lesson after the future driver has adjusted the mirrors of the truck.

OPEN RESEARCH

Beside the adjustment of the mirrors there is one remaining lack of knowledge. Who is able to tell the truck driver at what time in a special traffic situation it will make sense to have a look to the mirror(s). This is a result of a pilot study made in Berlin. Truck drivers were equipped with a helmet camera to follow the eyes movement (see Figure 13). The first results of the analysis of these videos were interesting. Some truck drivers had a first look to the wide angled mirror in a right turning situation when the truck had already done a movement of 45 degrees of the intended 90 degrees. With such a use of mirrors there are two possibilities. First there is no vulnerable road user (VRU) having a conflict with this truck. The second is more problematic. The VRU will be already under the truck. To have a first look to the class IV mirror in this situation is too late.

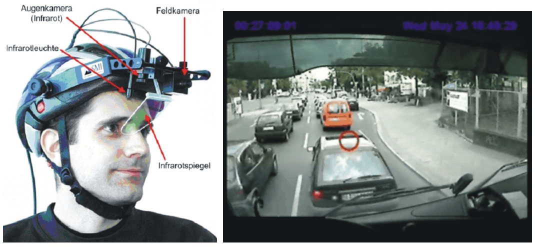

Figure 13. Example of eye tracking system used for truck drivers [4]

CONCLUSIONS

The new mirror regulation 2003/97/EC is beyond any dispute a good regulation to reduce the blind spot of trucks. But the equipment of trucks is only the first step. The second step just starts with the orientation help for adjustment of the mirrors. The use of the adjustment help has to be accompanied by a transfer of mirror knowledge to the driver. It is necessary to know for the driver what the mirrors are able to show. Where is a vulnerable road user located when it is shown by a mirror. Are there some remaining blind spots? Where are these blind spots? What is a good way for the driver to use the mirror system of the truck? Only if the driver got the complete knowledge he or she will be able to use the mirror system in a perfect way.

There is currently not enough knowledge how to use the mirrors in different traffic situations. An additional study is necessary. The results could be easily given to European truck drivers by using the directive 2003/57/EC which requires within five years 35h of educations for truck drivers. The knowledge how to handle mirrors in different traffic situations may reduce the number accidents caused from the blind spot problem in the future. This is possible independent from the equipment (old or new mirror system). The knowledge should be transferred to all truck drivers.

The OEMs are developing also new assistance systems to reduce the blind spot problems of trucks. But the current truck fleet is neither equipped with such an assistance system nor are these systems available for all new trucks. It will take a lot more time until all trucks will have this kind of equipment.

REFERENCES

[1] 71/127/EC, European directive for rear view mirrors of motorised vehicles, April 1996

[2] 2003/97/EC, European directive for devices for indirect vision and of vehicles equipped with these devices, 29. January 2004

[3] 2007/38/EC, European directive for retrofitting of mirrors of heavy goods vehicles registered in the community, 10. July 2007

[4] Leser, HJ; Icke, St.: Right-Turning Lorries and Cyclists - Results of Accident Analyses and Field Trial in Berlin, DEKRA Symposium, 13. October 2006, Neumünster, Germany

[5] Majer, A.: Analyse des Sichtbereiches am Lkw (Analysis of the Visibility Area at a Truck), student research project, Berufsakademie Horb, January 2008, Germany

NEW REQUIREMENTS TO THE EMERGENCY EXITS OF BUSES

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Paper Number: 09-0181

ABSTACT

Based on certain assumptions, the requirements of emergency exits on buses and coaches are specified in ECE Regulation No.107. Different accident situations, real accidents proved that some of the original assumptions are not valid, so it is necessary to reformulate them. Accident statistics – containing some hundreds bus accidents – and in depth accident analysis were studied, concentrating on the evacuation of buses and the rescue possibilities of the bus occupants. Certain results and conclusions of evacuation tests are also considered which show the capabilities and limitations of different groups of passengers (men-women, young or elderly people, etc.) when evacuating the bus through different kind of emergency exits. The new assumptions to specify the required number and location of emergency exits of buses are based on the following perception: the usability of the individual emergency exits are different in different bus categories (e.g. low floor city bus, high-decker tourist coach, etc.) or even in one category (lower or upper level of a double-decker bus) and also in different accident situations (e.g. frontal collision, rollover, fire, etc.) The next step is to specify the "usability" in technical, measurable terms. The paper proposes four aspects, shortly: to open the exit, to creep through the exit, to step/jump down from the bus and the possibility of the continuous use of the exit. Some possible measures are proposed to these aspects. On the basis of these aspects, all the emergency exits may be qualified (good, acceptable, poor, not usable) in every bus categories and every accident situation. Finally the required number of emergency exits (how many good, acceptable exit) could be specified which shall be provided for the occupants in every essential accident situation.

INTRODUCTION

In the case of an accident situation the passengers of a bus have to leave the vehicle as quickly as possible. To do that they use every kind of exit available for the evacuation. The following exits were considered to serve as emergency exits (EE): service door; emergency door; door of the driver's cab; side window and rear window designated as emergency window; escape hatch and rear wall door in case of small buses. The existing requirements for the bus EE-s are summarized in the UN-ECE Regulation 107, (R.107) among a lot of other general safety requirements of buses. The EE's requirements are grouped as follows:

a) required number of EE-s
b) their location and distribution
c) the required minimum dimensions
d) required access to EE-s
e) technical requirements of their operation.

These requirements are in force since 30 years and during this period only a few, small corrections were made to improve them for better understanding. But during this period a lot of experiences were collected about the usability of different EE-s and some very serious accidents – fire in the bus, many injured passengers on board, panic among the passengers, etc. when the passengers could not evacuate the bus – called the attention to the problems of the existing regulation. The need for improving the regulation has been raised in different working and expert groups of the UN-ECE organization in Geneva. This paper tries to contribute to the discussion of this problem, concentrating on the subject groups "a" and "b" mentioned above.

PRINCIPLES OF THE EXISTING REQUIREMENTS

When working on the requirements of EE-s in the bus regulation – 30 years ago – certain assumptions were used as starting points. (It has to be mentioned: at that time the experts did not have too many information, experience on that field) Of course these assumptions are not mentioned in the regulation, but their consequences may be recognized:

- only that accident situation was considered when the bus is standing on its wheel.
- the number of EE-s shall be proportional somehow to the passenger capacity of the bus
- every separated compartment – passenger and driver compartment – shall have EE. (This requirement has special importance in articulated and double deck buses)
- the number of EE-s shall be closely the same on the two sides of the bus, as well as in the front and rear half of the vehicle.
- all kind of EE-s have the same usability, they are equivalent to each other in all emergency situations.

- a certain EE type (e.g. side window) has the same usability in all bus categories (e.g. mini-bus or the upper part of a double deck bus)
- a certain EE type (e.g. escape hatch) has the same usability in every major accident situations (e.g. the bus is standing on its wheel or on its roof)

Figure 1. General collapse of the superstructure in rollover

At the beginning it was not considered, but later it became evident that the EE-s can be used only if the bodywork of the bus – at least in the surroundings of the EE – is not strongly damaged. The large scale structural deformations generally prevent to access, to operate and use the EE. Figure 1. gives examples about the total collapse of the superstructure in rollover accidents. These pictures prove that in these cases it is meaningless to talk about EE-s. Figure 2. shows examples when only one, or just a few EE-s can not be used because of strong, local structural deformations.

Figure 2. Local large-scale deformation of the bodywork

ACCIDENT SITUATIONS TO BE CONSIDERED

When improving the requirements of EE-s, some of the original principles mentioned above should be reconsidered. One of the major issues is the list of the major accident situations to be considered, in which the EE-s can help, must help in the evacuation of the bus. These are:

- rollover, considering the possible major situations after the accident (until one complete rotation),
- front impact, considering the total or partial impacts, too,
- side impacts, considering both sides and only heavy vehicles as impacting partner
- rear impact, considering heavy vehicles when impacting the full rear wall.
- fire in the bus, considering different locations of fire initiation
- bus in shallow water (not completely sunk)
- combined accidents (the combination of the above said accidents)
- special accidents.

Two of these accident situations need particular attention. The rollover is the most complex accident. More final bus positions may occur, but at least four basic situations shall be considered. The bus stops on its one side, or on the other one, may be on its roof or on its wheels. This last situation means that the rollover accident contains the basic evacuation situation, too, when the bus is just standing on its wheels.

The other important accident situation is the fire. The fire brings a very important, essential parameter into the evacuation process: the time limitation. The fire generates smoke, poisoning gases and heat which can block the passengers in the evacuation. It is interesting to mention that sometimes the fire is the consequence of a rollover or a frontal collision (combined accident situation). In a rollover statistics containing 383 bus rollover accidents, 12 times the rollover was followed by a fire and the bus completely burned out. Among 256 frontal collisions it happened 14 times. These are very severe accidents with extremely high mortality and casualty rate.

Figure 3. Fire tests with complete bus type IK255

Fire tests were carried out in Hungary with three complete buses (type IK 255 and IK 415) simulating five fire sources. Figure 3. shows one test when the whole fire propagation process was observed and studied with the measurement of temperature and some poisoning gas concentration increasing. [1] The source of fire was in the closed box of the heating device, under the floor. The measured values (CO, HCl, HCN gas concentrations; temperatures T_{far} far from the fire source and T_c close to that) are presented on Figure 4. Without detailed discussion of the test results it may be said that from the first possible observation of the fire, the available time for evacuation was in the range of 200-300 sec. The smoke density was not measured, but visually detected by filming it was developed very rapidly. The critical values of gas concentrations are marked by a horizontal line on the left side of the diagram. The life danger is mainly due to the gas and smoke concentration and less to the high temperature.

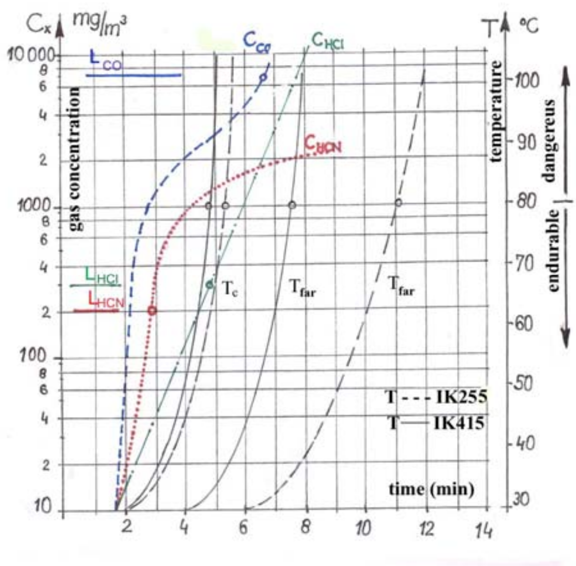


Figure 4. Increasing of temperature and poisoning gas concentrations in the bus fire.

THE USABILITY OF DIFFERENT EMERGENCY EXITS

Figure 5. Usability of side emergency window

The assumption that the usability of a certain type of EE is the same in every bus categories is not true. Figure 5. shows the usability of the side emergency windows in case of double deck (DD) bus comparing the upper and lower level passenger compartment (after a frontal collision) and also the situation on a high (but single) deck (HD) tourist coach. The side emergency window is a very useful exit in the case of the lower level of a DD bus or on low floor buses, but they cannot be used in the case of the upper level of a DD bus or on a HD coach.

The assumption that the usability of a certain type of EE is the same in different accident situation is also not true. Figure 6. shows some examples. The escape hatches are absolutely not usable when the bus is laying on its roof. The side emergency windows are well usable (on both side) in this situation in large buses, but they are almost useless in small buses. For small buses the rear wall door is very useful in this case.

Figure 6. Usability of escape hatches (?)

The assumption that all kind of EE-s have the same usability (they are equivalent and replaceable) is also not valid. Figure 7. gives a very clear argument considering and comparing all the possible (and required) EE-s on DD coaches, e.g. side windows, escape hatches, rear wall window, service door and the door of the driver compartment.

There is one important question to be raised. In the existing regulation the windscreen is not considered as possible EE. The reason of that is that the windscreens are made from laminated glass and therefore it is not breakable. But in the last few years a very effective new technology has been developed and already used by the firemen: to cut the laminated glass with a small (4 kg of mass) electric rescue saw. It could be placed in the driver's compartment. (similarly to the fire extinguisher) and if necessary, used by the driver. Figure 8. shows examples, when this device was used after an accident by the fire brigade. It can be seen easily that the windscreen is one of the best, most usable EE in many accident situation, so in the future it should be considered.

Figure 7. Different emergency exits do not have the same usability

Figure 8. Using the windscreen as emergency exit by cutting it.

The usability could be an important principle when reconsidering the EE-s in buses. But from regulatory point of view, the usability shall be a quantitative, measurable, objective term (objective as it can be). Of course there are many possibilities to do that, in the following one method will be shown and discussed.

POSSIBLE SPECIFICATION OF USABILITY

First of all a classification should be set up related to the usability of EE-s. The usability could be very good, good, acceptable, bad, very bad and unusable. This last category is clear, the EE is unusable if in the given accident situation the EE cannot be opened because the bus is laying on that side, where the EE is located. The technical aspects of the classification could be:

- Opening of the EE includes the following: to find the exit, to approach it, to understand its operation and to open it.
- Climbing up to EE when use it by a passenger
- Jumping down from EE (from the bus) when use it.
- Possibility of the continuous use by the passengers, following each other, considering children, elderly people and injured persons, too.

Table 1. summarizes the possible technical parameters of the usability. When proposing this specifications and figures, certain assumptions were used:

- Certain, but not well defined positive co-operation is presumed among the passengers when evacuating the bus.
- Certain, but not well defined outside help is presumed (but not organized, well trained help) e.g. given by the driver, or by one or two younger, stronger male passengers using first the EE, or by outside people being close to the accident.
- The assigned side-wall emergency windows may be used without the very negative effect of the sharp, pointed remaining parts of the broken window. This negative effect can be avoided by not using breakable side window as emergency exit (there are more technical solutions) or clean the window frame very carefully (it takes too much time) or cover the window frame by protective rag, see on Figure 1. (The problem is that generally the protective rag is not near at hand)

Table 1. Measures of usability

Usability Technical aspect	Very good	Good	Acceptable	Weak	Very weak	Unusable
Opening [(1)]	done by the driver	simple, easy, small effort by passenger	simple, small knowledge and effort by passenger	considerable effort and skill is needed by passenger	outside help is needed	In the given situation it is put out of action[(3)]
Climbing up to the exit when use it	no need	no need	less than [1 m]	more than [1 m]	more than [1,5 m]	
Jumping down from the exit when use it	no need	less than [1 m]	less than [1,8 m]	less than [1,8 m]	more than [1,8 m]	
Possibility of continues use [(2)]	possible, no obstacles, difficulties	possible with small help	possible with inner and outside help	possible with inside and outside help	not possible	

(1) opening includes: to find the exit, to understand its operation and to open it

(2) considering children, elderly passengers and injured persons, too, following each other in the evacuation

(3) e.g. when the bus is laying on that side where the exit is located

RESULTS OF EVACUATION TESTS

After preparing (1974) and putting into force (1976) the EE's requirements in R.107, some tests were made in different countries to check the usability of the EE-s. These test results were not compared, discussed and evaluated together and were forgotten by the passing time. Now some of them will be shown again.

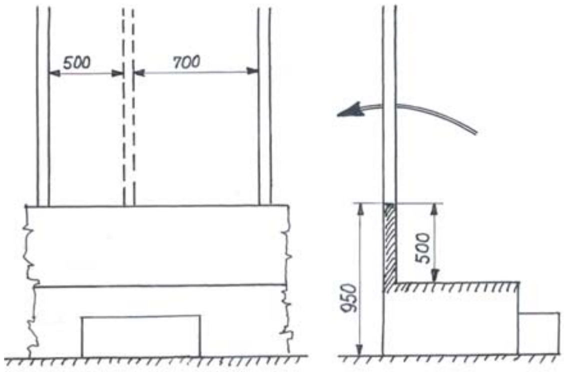


Figure 9. Evacuation test arrangement in Cranfield.

In UK, Cranfield Inst. Of Technology made a test with 100 voluntary elderly people (their average age was 73 years) to pass through a simulation of side emergency window [2] Figure 9. shows the test arrangement. They simulated 3 different width of the window (500 mm, 700 mm and 1200 mm) The main conclusion was surprising: 44% of the sample were unable to exit through the window simulation, they refused to make a trial. They did not find difference between the 500 mm and 700 mm width, but the 1200 mm shortened the exit time by 26%. They tested the required height of the window, it started from 950 mm up to 1400 mm above the waistrail. The average evacuation time for one passenger (who passed the test was 10 sec (500 mm width) and 7 sec (1200 width). It has to be mentioned, that the “geometry” of this test arrangement was not “realistic”: the inside height of the waistrail is generally in the range of 600-800 mm (instead of 500 mm) and the outside height above the road is in the range of 1600-1800 mm (instead of 950 mm)

Another interesting evacuation test series from UK was made in the University of Technology, Loughborough [3]. They used existing coach (passenger capacity 53, floor height 1200 mm, waistrail height to the floor/road level 750/1860 mm) They tested the emergency window (hinged type) and emergency door (also hinged type) They reproduced and tested also the emergency door and window with the required minimum dimensions according to the regulation. (see Figure 10).

They performed the test with and without outside podium having a height above the ground 600 mm for the door and 1200 mm for the window. (see Figure 11.) They used three samples of passengers differing in age (Group1: 7-15 years; Group 2: 20-45 years; Group 3: 60-75 years) There were 48 persons in every group, 50% male/female. The tests with podium here are also not realistic. The different passenger motions are shown on Figure 11. and Figure 12. when there is, or there is no podium. The report contains a lot of test results, some interesting, characteristics results are given in Table 2, showing the evacuation time of 48 passengers..

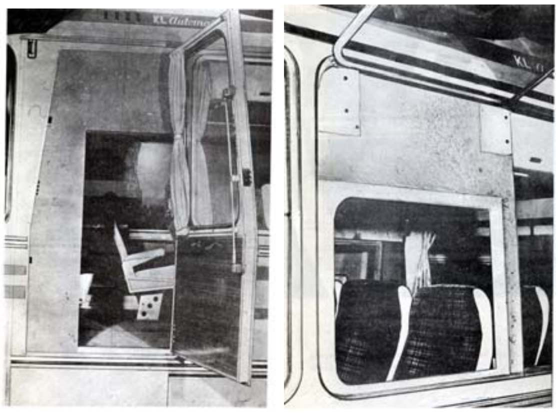


Figure 10. Normal and minimum size exits used in the Loughborough tests.

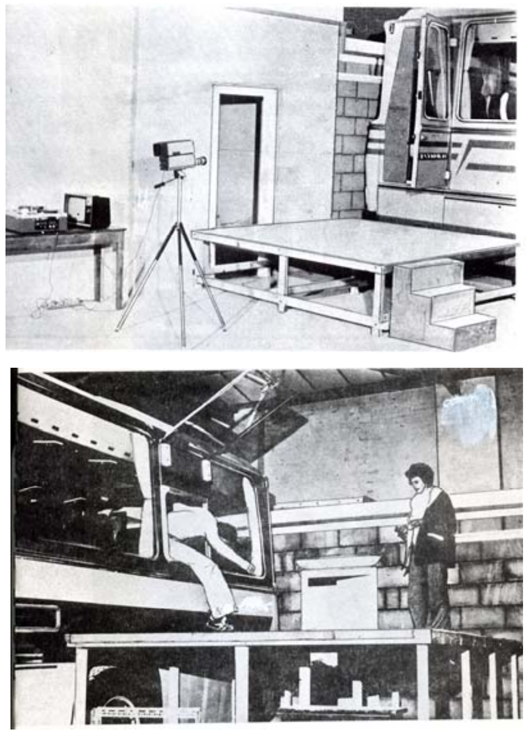


Figure 11. The tested versions of EE-s with outside podium..

Table 2. Evacuation times

Way of evacuation	Group 1	Group 2	Group 3
Emergency door with podium	120 sec	150 sec	240 sec
Emergency door without podium	210 sec	210 sec	*
Emergency window with podium	270 sec	330 sec	600 sec
Emergency window without podium	**	540 sec	**

* not all the passengers could make the test
** Group 1 and 3 could not perform this test

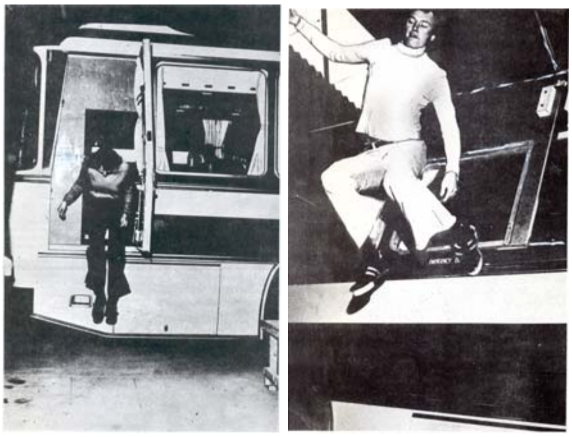


Figure 12. Leaving the bus without podium

The ratios between some interesting issues:

- Male/female in the same age group 1: (1,2-1,5)
- Faster 12/slower 12 passengers 1: (1,2-1,6)
- Emergency door/emergency window 1: (2,2-3,5)

There was a test series carried out in Germany, too [4]. Two scheduled service buses and two coaches were used in the evacuation test with two kind of passenger samples: children aged between 8-10 years and adults. The vehicles were standing on its wheels. When testing emergency windows, outside podiums were used. No details about the vehicle geometry and passenger capacity. The complete measured evacuation times are given in Table 3. (all the passengers leaving the bus) Two interesting statements from the document:

- The most dangerous accident situation is: the bus is burning while lying on its side.
- Possible increase of evacuation effectiveness needs at least two exit systems (instead of one) with increased capacity: when the vehicle is in standing position or lying on its side.

Table 3. Evacuation times

Way of evacuation	Service bus		Coach	
	children	adults	children	adults
2 service doors (SD) (1)	30 sec	30 sec	40 sec	30 sec
2 emergency windows (SW) (3)	-	52 sec	-	52 sec (2)
2 SD + 2 SW	-	15 esc	-	24 sec (4)

(1) 2/3 of the occupants used the rear service door
(2) Half of the groups left the vehicle
(3) Braking the window and cleaning an exit hole took 15 sec
(4) 2/3 of the occupants used the doors

We also made evacuation tests in Hungary, in the Research Institute AUTOKUT [1] The used coach had a passenger capacity of 45, floor height 940 mm, waistrail height above the road 1750 mm, 2 service doors (the rear one was transformed for emergency door, too.) Two groups of passengers were used: professional, trained firemen, age 20-40 and adult persons in age 25-45. (15 females and 30 males) The bus was standing on its wheels, the "passengers" knew what to do after the signal "fire", the firemen wore light uniform, and the adult persons wore summer clothes without hand baggage. The measured complete evacuation times are given in Table 4.

Table 4. Evacuation times

Way of evacuation	Passenger group	Number of tests	Evacuation time
Front service door	firemen	2	25-28
Front service door	adults	2	37-40
Real service door	adults	1	40
Two service doors	adults	1 Table II.	20
Rear emergency door	adults	1	54
Side emergency windows	firemen	1	10

In this last case the firemen kicked out – in the same moment – all the side windows together with the rubber mounting on both sides of the bus and jumped out trough the empty window frames, see Figure 13.

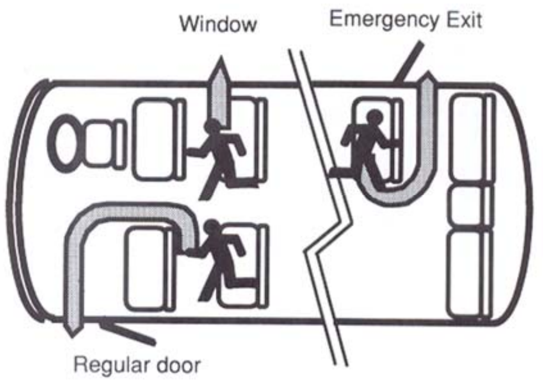
Figure 13. Evacuation tests in Hungary: service door and side window

Test was carried out with a 30 years female to break the window and leave the bus through the emergency window. The woman was afraid of climbing up and jumping through the window which had sharp glass fragments on the waistrail, therefore she needed help from outside. The measured times for one test:

- Finding and getting the hammer, cracking the glass: 15 sec
- Creating a "free exit" with appropriate size, additional: 25 sec
- Leaving the bus with outside help, additional: 50 sec

An interesting evacuation test series were carried out in Japan, JAMA [5]. They used a high deck coach and tested the use of service door, emergency door and emergency side window as EE. The passenger sample was built up from 6 schoolchildren (8-12 years) 12 adults (20-28 years) and 6 elderly people (66-73 years) Figure 14. shows the test bus and the three kinds of tests. The emergency window was not a breakable one, but sliding type. If the test passengers thought that it is dangerous to jump down to the ground either from the emergency door (floor height ≈ 1500 mm) or from the emergency window (waistrail height 2300 mm) they could use an outside podium (1500 mm high). They measured the evacuation time of every individual from starting the process (standing up from the seat) to the end (being outside, on the ground or on the podium). They repeated the test with every person three times. Some results:

- The evacuation time of one passenger is around 10 sec, no considerable difference between the age groups or between emergency door or window
- The evacuation time through service door is 7 sec for children and adults, and 10 sec again for elderly people.
- ¾ of the evacuation time was needed to find and get the EE, to understand its operation and to open it.
- At the first trial no one of the children and only half of the elderly people could perform the test with the emergency door. They could not open it.



50 sec

Figure 14. The coach used for evacuation tests in Japan

EVALUATION OF DIFFERENT EMERGENCY EXITS

Accepting the new assumptions:

- The usability of the same type of EE could be different in different accident situations and in different bus categories (or in the same category, too)
- The usability of the different types of EE are not equal in different accident situation
- The usability of one given EE could be different in different accident situations.

Table 5. The bus is standing on its wheels

Evacuation through	Large, single deck bus		Double deck bus		Small bus
	Low deck	High deck	Lower deck	Upper deck	
SD	very good	very good	very good	-	very good
ED	good	good	-	good	-
RD	-	-	-	-	good
SW	good	acceptable	good	very weak	good
RW	acceptable	weak	-	very weak	unusable
EH	very weak	very weak	-	very weak	acceptable
DD	weak	weak	weak	-	weak
WS	acceptable	acceptable	acceptable	very weak	-

The used symbols:

SD	service door	SW	side-wall emergency window
ED	emergency door	RW	rear-wall emergency window
RD	rear-wall door	EH	escape hatch
DD	driver's cab door	WS	windscreen

The different types of EE-s in different accident situations should be evaluated based on the specifications proposed in Table 1. Table 5. summarizes the usability of different EE-s when the bus is standing on its wheels. In case of large, single deck buses:

"low deck" means: waistrail height above the road is less than 1,8 m;

"high deck" means: waistrail height above the road is more than 1,8 m.

The upper deck of a DD vehicle is rather poor from the point of view of EE-s. May be the staircase communicating to the lower deck (to service doors) may be accepted as a "good" route, but only when the vehicle is in standing position.

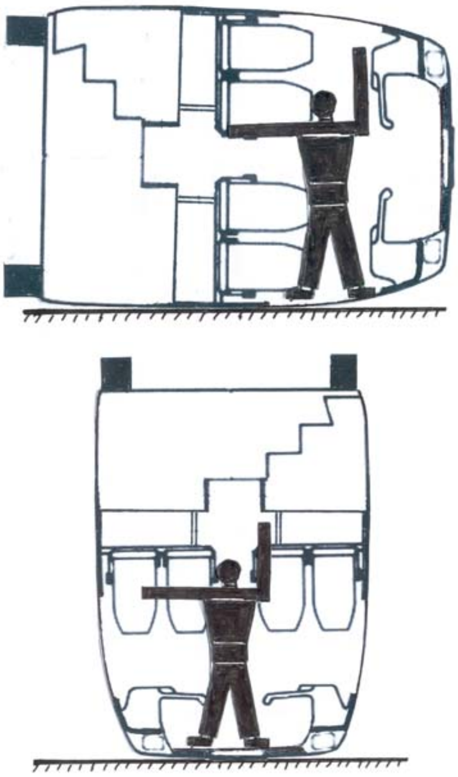


Figure15. The bus in different final positions.

Table 6. shows the situation when the bus is lying on its door side, while Table VII. the other side position. Figure 15. shows the bus in different final positions, lying on its side or on its roof. The sketches are scaled and the passenger contour represents an 1,7 m tall person, just to give an impression about the usability of different EE-s.

Table 6. Bus is lying on its door side

Evacua-tion through	Large, single deck bus		Double deck bus		Small bus
	Low deck	High deck	Lower deck	Upper deck	
SD	unusable	unusable	unusable	-	unusable
ED	very weak	very weak	-	very weak	-
RD	-	-	-	-	good
SW	very weak	very weak	very weak	very weak	acceptable
RW	good	good	-	good	-
EH	very good	very good	-	very good	good
DD	very weak	very weak	very weak	-	very weak
WS	very good	very good	very good	very good	-

Table 7. Bus is lying on the other side

Evacua-tion through	Large, single deck bus		Double deck bus		Small bus
	Low deck	High deck	Lower deck	Upper deck	
SD	weak	weak	weak	-	good
ED	unusable	unusable	-	unusable	-
RD	-	-	-	-	good
SW	very weak	very weak	very weak	very weak	acceptable
RW	good	good	-	good	-
EH	very good	very good	-	very good	good
DD	unusable	unusable	unusable	-	unusable
WS	very good	very good	very good	very good	-

Finally Table 8. shows the usability of different EE-s when the bus is standing on its roof. These four Tables (5 – 8) illustrate well the wide range of usability of the different EE-s in different vehicles and accident situations. For example the service door could be evaluated as "very good"; "good"; "weak"; or "unusable".

Table 8. Bus is standing on its roof

Evacuation through	Large, single deck bus		Double deck bus		Small bus
	Low deck	High deck	Lower deck	Upper deck	
SD	good	good	acceptable	-	very good
ED	good	good	-	good	-
RD	-	-	-	-	good
SW	good	good	good	good	good
RW	good	good	-	good	unusable
EH	unusable	unusable	-	unusable	unusable
DD	acceptable	acceptable	acceptable	-	weak
WS	very good	very good	-	very good	-

POSSIBLE SET UP OF NEW REQUIREMENTS

To determine the required number and location of EE-s the following should be considered:

- the passenger capacity of the bus (or the separated passenger compartments)
- possible major after-accident positions of the bus
- usability of different EE-s in different bus positions and in different bus categories
- limited time in case of fire.

From the bus fire tests it may be said that in case of fire the available time for successful evacuation is not more than 200-300 sec. The different evacuation tests showed that 45-48 passengers may leave the bus (when it is standing on its wheels, passengers in normal position, no panic, no injured passengers, everybody knows what to do)

- through one service door (very good usability) in 40-80 sec
- through the emergency door (good usability) in 60-210 sec
- through one emergency window (acceptable usability) in 360-900 sec

The proposed requirement for the minimum number and location of EE-s is the following:

a) every separated passenger compartment in every essential bus position (standing on its wheel or on its roof, lying on its sides = 4 positions) shall have:
   - up to 20 passengers min. 2 at least "acceptable" EE-s, among which 1 is "good" or "very good"
   - for 21-70 passengers min. 6, at least "acceptable" EE-s, among which min. 2 is "good" or "very good"
   - above 70 passengers, additionally two at least "acceptable" EE-s are required

b) above the required number of "good" or "very good" EE-s, every extra "good" or "very good" one shall be considered as two "acceptable" EE-s.

c) the staircase to the upper deck in DD vehicles or the joint section between the two parts of articulated vehicles may be connected as a "good" EE when the vehicle is standing on its wheels.

As an example, let us check a 12 m long tourist coach with 53 passenger capacity and waistrail height above the road 1,7 m and above the seat-floor 0,8 m. The coach has the following EE-s: 2 service doors; 1 emergency door; 3 escape hatches; 1 rear-wall emergency window; 2-2 side-wall emergency windows and 1 one windscreen.

The required number of EE-s is: minimum 6 "acceptable" EE-s among which at least 2 are "good" or "very good" in every essential bus position. Checking these positions, the results are shown in Table 9.:

Table 9. Evaluation of requirements

EE-s	Standing on the		Lying on the	
	wheels	roof	door side	other side
2 SD	very good	good	-	-
1 ED	good	good	-	-
4 SW	acceptable	good	-	-
1 RW	acceptable	good	good	good
3 EH	-	-	very good	very good
1 WS	acceptable	very good	good	acceptable*
good or very good	3	9	5	4
acceptable	6	2	-	1
requirements	met	met	met	met

* the driver's cab should be considered

REMARKS

It is interesting to underline that the role of the emergency side windows is underrated, because they cannot be used in two and half accident situations, (the half is standing on its wheels but having high waistrail position). The breakable emergency windows may be omitted in the future, because there usability is questionable. In the same time the windscreen has high importance, because it can be used in every position and in three cases its usability is good or very good. (To equip the bus with a glass cutting device and skill the driver about its use is the required condition.)

The EE-s of DD vehicles shall be studied in detail. The lower deck is in vulnerable position when the bus is lying on its sides and the upper deck when it is standing on its wheels. These problems shall be solved in the future.

Finally one more interesting problem, which strongly belongs to the usability of EE-s. All EE-s shall be so designed and equipped with handles, handholds, grips and special devices which can help to the passengers in using the EE in all essential bus positions. The access to the EE-s in every position is also important, considering that the passengers could be in very difficult, strange position, when the bus is not standing on its wheels. [5] [6]

REFERENCES

[1] Bus fire and evacuation tests. Informal doc. on the 91st meeting of GRSG. No GRSG-91-10. (Presented by Hungary) 2006 Manuscript, UN-ECE, Geneva, secretariat of WP.29

[2] Investigation into the ability of elderly people in climbing out of simulated bus emergency exits. Project report, March, 1974. Industrial Ergonomics. Cranfield Institute of Technology. Manuscript. (Presented in GRSA)

[3] Emergency exits from public service vehicles. Institute for Consumer Ergonomics, University of Technology, Loughborough, Leicestershire. March, 1976. Study report, manuscript (presented in GRSA)

[4] Evacuation of bus passengers: emergency exit systems. TRANS/SC1/WP.29 /GRSA/R.105 December, 1985 (Presented by the Federal Republic of Germany)

[5] Yukio Shiosoka – Teekeshi Kuboike. Research on the evacuation readiness of bus crews

and passengers. Investigation of current bus exit performance and effect of easy-to-understand emergency exit display. 15th ESV conference, Melbourne 1996. Vol.2. p.1854-1860

[6]] Sharon Cook – Dean Southal. PSV emergency exits: passenger behaviour and exit design. ICE Ergonomics Ltd., Loughborough University, Leicestershire. September, 1996. Research report, ordered by DoT. Manuscript.

INJURY MECHANISMS TO MASS TRANSIT BUS PASSENGERS DURING FRONTAL, SIDE AND REAR IMPACT CRASH SCENARIOS.

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ABSTRACT

According to the Traffic Safety Facts reports from 1999-2003, an average of 40 fatalities and 18,430 injuries of bus occupants occurred per year. The objectives of this research are to characterize the kinematics and injury mechanisms of bus passengers during typical frontal, side and rear impact conditions. Accident data from the traffic Safety Fact Reports, Buses Involved in Fatal Accidents Report and Transit Agency data were review to define typical crash scenarios. A detailed finite element model of a low floor transit bus was used to calculate the crash pulses at the passenger compartment for typical frontal, side and rear impact conditions. A series of sled tests with 5^{th}, 50^{th} and 95^{th} percentile occupants were conducted at NIAR's Crash Dynamics Laboratory in order to study the occupant kinematics and to identify injury mechanisms to bus passengers.

The results of this study show that the most common injury mechanisms to bus passengers are head (HIC) and neck injuries (neck extension, flexion and compression). These injuries are due to body-body contact between unrestrained passengers and/or body-to-seat structure contacts.

INTRODUCTION

According to the Standard Bus Procurement Guidelines [1], the passenger seating arrangements in mass transit buses shall be such that seating capacity is maximized and that it complies with the requirements defined in section 5.4.5.1. As shown in figure 1 there are several possibilities for the arrangement of seats. Passenger seats can be arranged in a transverse, forward facing configuration or arranged in longitudinal rows facing the centerline of the bus (perimeter seating configuration). A limited number of rearward facing seats can be used with the expressed approval of the procurement agency. Also it is possible to have a combination of forward facing and perimeter seating arrangements. The Procuring agency recognizes that ramp location, foot room, hip-to-knee room, doorway type and width, seat construction, floor level type, seat spacing requirements, etc. ultimately affect seating capacity and layout.

The objectives of this research are to characterize the kinematics and injury mechanisms of bus passengers during typical frontal, side and rear impact conditions. Accident data from the traffic Safety Fact Reports, Buses Involved in Fatal Accidents Report and Transit Agency data were review to define typical crash scenarios. A detailed finite element model of a low floor transit bus was used to calculate the crash pulses at the passenger compartment for typical frontal, side and rear impact conditions. A series of sled tests with 5^{th}, 50^{th} and 95^{th} percentile occupants were conducted at NIAR's Crash Dynamics Laboratory in order to study the occupant kinematics and to identify injury mechanisms to bus passengers.

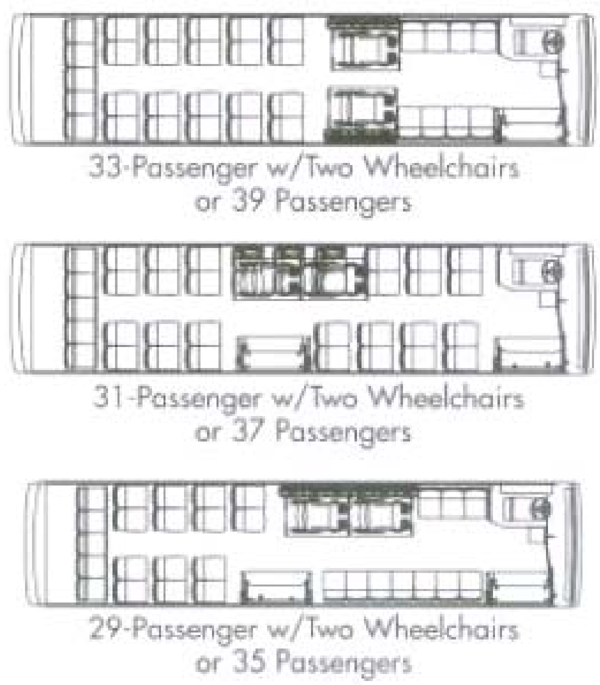

Figure 1. Typical Mass Transit Bus Seat Arrangement

ACCIDENT DATABASES REVIEW

This section presents a summary of statistics on bus crashes. Bus crash data was obtained from the Traffic Safety Facts report [2]-[3], years 1999-2003, and the Buses Involved in Fatal Accidents report [4]-[2], years 1999-2001.This statistical review was performed to gain insight into the types of bus crash mechanisms that result in occupant injuries and fatalities. As documented in

Reference [2], there is not a standard for collecting crash data for mass transit buses. Furthermore, not all agencies collect crash data. Based on inquiries to transit agencies by

NIAR, the experiences of the authors in Reference [2] and the scope of this project, NIAR researchers made the decision to proceed with the available crash data in the Traffic Safety Facts Reports and the Buses Involved in Fatal Accidents (BIFA) reports.

Traffic Safety Facts Report Bus Data

The Traffic Safety Facts report is an annual compilation of motor vehicle crash data presented by the National Highway Traffic Safety Administration (NHTSA). Data from the Fatality Analysis Reporting System (FARS) and the National Automotive Sampling System General Estimates System (GES) is combined to create Traffic Safety Facts. The FARS database, established in 1975, records data from traffic crashes involving a fatality. The GES database, established in 1988, records data from a nationally representative sample of police reported crashes of all severities, including those that result in death, injury or property damage [2, 3].

In the Traffic Safety Reports, buses are defined as "Large motor vehicles used to carry more than ten passengers, including school buses, inter-city buses, and transit buses". Data presented in the Traffic Safety Report is often grouped by crash severity, with the following categories: (1) Fatal Crash. A police-reported crash involving a motor vehicle in transport on a traffic way in which at least one person dies within 30 days of the crash. (2) Injury Crash. A police-reported crash that involves a motor vehicle in transport on a traffic way in which no one died but at least one person was reported to have: (i) an incapacitating injury; (ii) a visible but not incapacitating injury; (iii) a possible, not visible injury; or (iv) an injury of unknown severity. The following is a summary of the vehicle data [2, 3]:

- Sixty four percent of bus crashes involving fatalities result from a frontal initial point of impact. Rear impacts account for 16% and side impacts account for 14%.

- The initial point of impact in bus crashes involving injuries is evenly distributed, with frontal accounting for 37%, side for 36% and rear for 25%.

- Rollover occurs in less than 3.1% of buses involved in crashes with fatalities, and 0.1% of buses involved in crashes with injuries.

- Fire occurs in less than 0.3% of buses involved in crashes with fatalities, and less than 0.05% of buses involved in crashes with injuries.

- Thirty eight percent of buses involved in fatal accidents are School Buses, 36% Transit Buses, 11% other, 9% Intercity, and 6% is unknown.

The following is a summary of the occupant data:

- An average of 40 bus occupants per year were killed and 18,430 injured from 1999-2003.

- Forty seven percent male and 53% female were killed. 51% male and 49% female were injured.

- School age occupants, ages 5-20, account for 24% of bus occupants killed.

- Occupants over the age of 55 years account for 43% of bus occupants killed.

- Sixty eight percent of bus occupant injuries occur during two vehicle crashes.

- Sixty one percent of bus occupant fatalities result from frontal crashes, 17% from side crashes and 9% from rear crashes.

- Thirty percent of bus occupant injuries result from side crashes, 33% from frontal crashes and 30% from rear crashes.

- Twenty eight percent of bus occupant fatalities result from occupant ejection, 53% from non-ejected fatal impacts and 19% were unknown.

- An average of 49 pedestrians and 9 pedal-cyclists per year are killed in crashes with buses.

- Forty percent of bus occupant injuries result from school bus crashes, 24% from intercity bus crashes and 23% from transit bus crashes.

- Thirty percent of bus occupant fatalities result from intercity bus crashes, 24% from school bus crashes and 14% from transit bus crashes.

- An average of 11 bus occupants per year are killed in two vehicle crashes while 162 occupants per year of other vehicles are killed.(102 occupants in passenger cars, 49 in light trucks 9 in motorcycles, 2 in large trucks).

- An average of 12,000 bus occupants per year is injured in two vehicle crashes while 8,800 occupants per year of other vehicles are injured. (6,000 in passenger cars and 2,800 in light trucks).

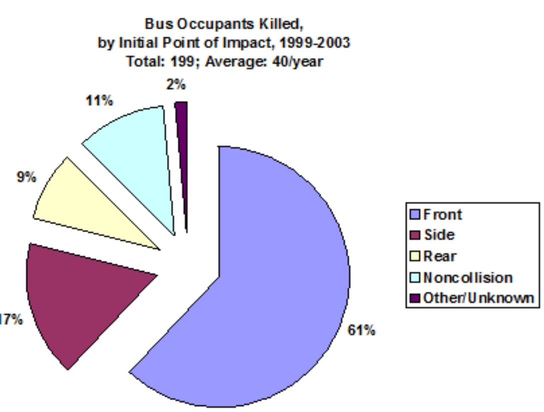

Figure 2. Bus Occupants Killed, by Initial Point of Impact, 1999-2003.

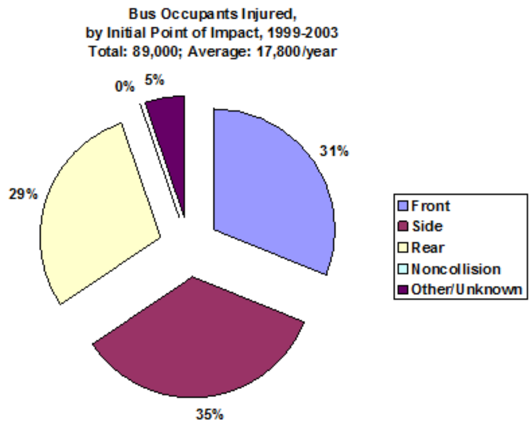

Figure 3. Bus Occupants Injured, by Initial Point of Impact, 1999-2003.

Buses Involved in Fatal Accident (BIFA) Report Data

The Buses Involved in Fatal Accidents (BIFA) report presents aggregate statistics for buses involved in traffic accidents, compiled by the University of Michigan Transportation Research Institute (UMTRI). The BIFA database is a census of all buses involved in a fatal accident in the United States, and provides coverage of buses recorded in the Fatality Analysis Reporting System (FARS) file. BIFA combines vehicle, accident, and occupant records from FARS with information about the physical configuration and operating authority of the bus from the BIFA survey. Modeled after UMTRI's Trucks Involved in Fatal Accidents (TIFA) program, the BIFA survey collects detailed information on all buses involved in all fatal traffic accidents. Buses are defined as motor vehicles with seating for nine or more, including the driver, that are not operated as personal transportation, and all motor vehicles with seating for 16 or more. The BIFA file is produced annually, beginning with the 1999 data year, from a survey of bus records extracted from the FARS file, compiled by the National Center for Statistics and Analysis at the National Highway Traffic Safety Administration [2, 4].

Accident, vehicle, and driver records that appear to involve a bus are selected from the FARS file. Police reports for each accident represented are requested from the appropriate states. The BIFA file is a census file, meaning there is one record for each bus involved in a fatal accident. The data presented in BIFA reports includes all bus type involvements. The data summarized in this paper is focused on transit bus involvements only. Involvements; counts of the buses involved in a fatal accident. Fatalities; counts of fatalities of occupants of bus and/or other vehicle involved. Transit; an entity providing passenger transportation over fixed, scheduled routes, within primarily urban geographical areas [2, 4].

The following is a summary of the BIFA report trends for transit buses for the period from 1999 to 2001:

- An average of 111 transit buses is involved in a fatal traffic accident each year.

- A total of 246 fatalities resulted from transit bus involvements from 1999-2000. 43% of the fatalities were drivers of other vehicles, 37% were pedestrians, and 13% percent were passengers of other vehicles.

- About 50% of fatal transit bus involvements occur during rush hour, from 6:00 to 9:59 a.m. and from 3:00 to 6:59 p.m.

- Eighty percent of transit bus fatal involvements occur during the work week. The lowest percentages of involvements, 7.8%, occur on Sunday.

- Eighty eight percent of fatal transit bus involvements occurred in urban environments.

- Sixty two percent of fatal transit bus involvements occur in daylight, 29% in dark but lighted conditions.

- Eighty two percent of fatal transit bus involvements occur on dry roadway surface conditions.

- Eighty nine percent of fatal involvements occur under "normal" weather conditions (i.e. no rain, snow, fog, or other adverse condition).

- Fifty eight percent of fatal transit bus involvements occur on local streets (township or municipality), 15% on state highways, and 8% on county roads.

- Fifty five percent of fatal transit bus involvements occur on 2 travel lanes.

- Sixty three percent of fatal transit bus involvements occurred between 25-35 mph.

- Ninety nine percent of single vehicle fatal transit bus involvements hit an object in the road.

- Eighty two percent of two vehicle fatal transit bus involvements on the same traffic-way, same direction resulted from a rear-end, bus struck.

- Eighty eight percent of two vehicle fatal transit bus involvements on the same traffic-way, different direction resulted from a head-on collision in the buses lane.

- Seventy seven percent of two vehicle fatal transit bus involvements on intersecting paths, both going straight resulted from the bus crashing into the side of the other vehicle.

- Fifty two percent of fatal transit bus by first harmful event, collision with non-fixed object, occurred with a motor vehicle in transport, 41% with other type non-motorist.

- Sixty eight percent of the fatal transit bus involvements by vehicle role in accident occurred from the vehicle striking the bus.

- Shorter, heavy-duty, transit buses accounted for 73% of fatal transit bus involvements.

- Buses accounted for 99% of fatal transit bus involvements.

- Low platform buses accounted for 65% of fatal transit bus involvements.

- Flat from buses accounted for 96% of fatal transit bus involvements.

- Thirty to forty foot buses accounted for 61% of fatal transit bus involvements.

- Buses with 25,001-30,000 lb. empty weights accounted for 70% of fatal transit bus involvements.

- Buses with gross weight greater than 33,001 lb accounted for 62% of fatal transit bus involvements.

- Eighty nine percent of fatal transit bus involvements were from buses with 2 axles.

- Fifty five percent of fatal transit bus involvements occurred in buses with a passenger seating capacity of 36-45, excluding the driver.

- Eighty eight percent of fatal transit bus involvements occurred in buses with no passenger restraints available, excluding the driver.

- Eighty four percent of fatal transit bus involvements occurred on local trips.

- For the most harmful event, collision with non-fixed object, of fatal transit bus involvements, 53% were with a vehicle in transport and 41% with a pedestrian.

Nearly two-thirds of bus occupant injuries occur during two vehicle crashes. The crash types are evenly distributed between side, frontal and rear. An average of 12,000 bus occupants per year are injured in two vehicle crashes while 8,800 occupants per year of other vehicles are injured. (6,000 in passenger cars and 2,800 in light trucks).

The majority of fatal crashes involving buses result from frontal crashes. Half of bus fatalities occur during either morning or evening rush hour. An average of 11 bus occupants per year is killed in two vehicle crashes while 162 occupants per year of other vehicles are killed. Transit bus crashes account for 14% of all bus occupant fatalities. The majority of transit bus fatalities occur during the work week, in urban environments, on dry roadway surfaces under normal weather conditions. Over half of fatal transit bus involvements occur on roadways with posted speed limits of 25-35 mph. Shorter, heavy-duty, low-floor transit buses account for the majority of fatal transit bus involvements. Most fatal transit bus involvements occurred on buses with 2 axles. Half of fatal transit bus involvements occurred on buses with a passenger seating capacity of 36-45 seats, excluding the driver. The majority of fatal transit bus involvements occurred in buses with no passenger restraints available, excluding the driver seat. An average of 49 pedestrians and 9 pedal-cyclists per year are killed in crashes with buses.

Based on the data reviewed, a typical transit bus accident occurred:

- in the afternoon, primarily during evening rush hour.

- under clear weather conditions

- on dry roadways

- in connection with another moving motor vehicle

- involving a rear-end or angle impact

- while the bus was either stopped or operating at a slow speed

CURRENT SEAT DESIGN STANDARDS

The passenger seat frame and its supporting structure shall be constructed and mounted so that space under the seat is maximized to increase wheelchair maneuvering room and is completely free of obstructions to facilitate cleaning [1]. The transverse seat structure shall be fully cantilevered from the sidewall with sufficient strength for the intended service. The lowest part of the seat assembly that is within 12 inches of the aisle shall be at least 10 inches above the floor. Foldaway or flip seats used in wheelchair securement areas, as well as, transverse seats mounted in locations at which cantilevered installation is precluded by design and/or structure, need not be cantilevered. The underside of the seat and the sidewall shall be configured to prevent debris accumulation and the transition from the seat underside to the bus sidewall to the floor cove radius shall be smooth. All transverse objects, including seat backs, modesty panels, and longitudinal seats, in front of forward facing seats shall not impart a compressive load in excess of 1,000 pounds onto the femur of passengers ranging in size from a 5th-percentile female to a 95th-percentile male during a 10g deceleration of the bus. This deceleration shall peak at .05 $\pm$ .015 seconds from initiation. Permanent deformation of the seat resulting from two 95th-percentile males striking the seat back during this 10g deceleration shall not exceed 2 inches, measured at the aisle side of the seat frame at height H. Seat back should not deflect more than 14 inches, measured at the top of the seat back, in a controlled manner to minimize passenger injury. Structural failure of any part of the seat or sidewall shall not introduce a laceration hazard [1].

The back of each transverse seat shall incorporate a handhold no less than 7/8 inch in diameter for standees and seat access/egress. The handhold shall not be a safety hazard during severe decelerations. The handhold shall extend above the seat back near the aisle so that standees shall have a convenient vertical assist, no less than 4 inches long that may be grasped with the full hand. This handhold shall not cause a standee using this assist to interfere with a seated 50th-percentile male passenger. The handhold shall also be usable by a 5th-percentile female, as well as by larger passengers, to assist with seat access/egress for either transverse seating position. The upper rear portion of the seat back and the seat back handhold immediately forward of transverse seats shall be padded and/or constructed of energy absorbing materials. During a 10g deceleration of the bus, the HIC number (as defined by SAE Standard J211a) shall not exceed 400 for passengers ranging in size from a 5th percentile female through a 95th percentile male. The seat back handhold may be deleted from seats that do not have another transverse seat directly behind and where vertical assist is provided in accordance with Section 5.4.5.2 [1]. Armrests shall not be included in the design of transverse seats. Longitudinal seats shall be the same general design as transverse seats but without seat back handholds. Longitudinal seats may be mounted on the wheelhouses. Armrests shall be included on the ends of each set of longitudinal seats except on the forward end of a seat set that is immediately to the rear of a transverse seat, the operator's barrier, or a modesty panel and these fixtures perform the function of restraining passengers from sliding forward off the seat. Armrests are not required on longitudinal seats located in the wheelchair parking area that fold up when the armrest on the adjacent fixed longitudinal seat is within 1-1/2 to 3-1/2 inches of the end of the seat cushion. Armrests shall be located from 7 to 9 inches above the seat cushion surface. The area between the armrest and the seat cushion shall be closed by a barrier or panel [1].

FRONTAL IMPACT INJURY MECHANISMS

A series of sled tests; as shown in figure 4; for a typical frontal crash were conducted for occupant sizes ranging from the 5th to the 95th percentile ATDs.

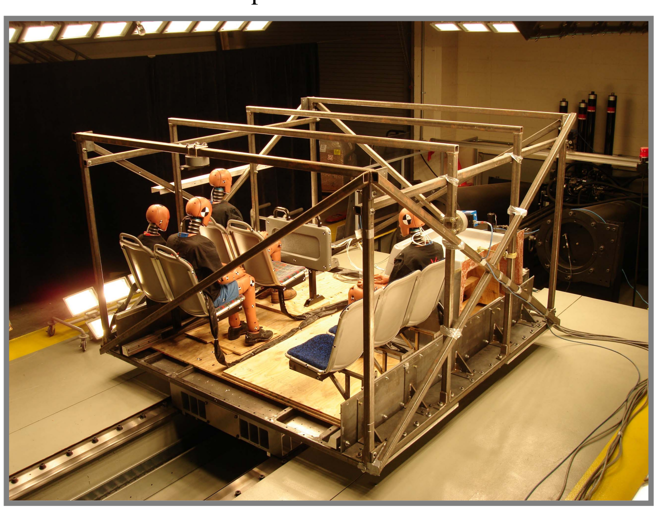

Figure 4. Frontal Sled Test Setup.

The objectives of these tests were to study the passenger kinematics and injury mechanisms for typical seat-to-seat and seat-to-divider layout configurations (see figure 6). Due to the number of tests conducted it was also possible to study the test-to-test variability of the occupant kinematics and injury mechanisms for the 50th and 95th percentile ATDs. The crash pulse for these tests was obtained from a previous structural analysis of typical frontal crashes [6]. Figure 5 shows the frontal crash configuration; a 30 mph head on collision between a low floor transit bus and a Dodge Caravan; and the pulse at the bus passenger compartment used for the testing.

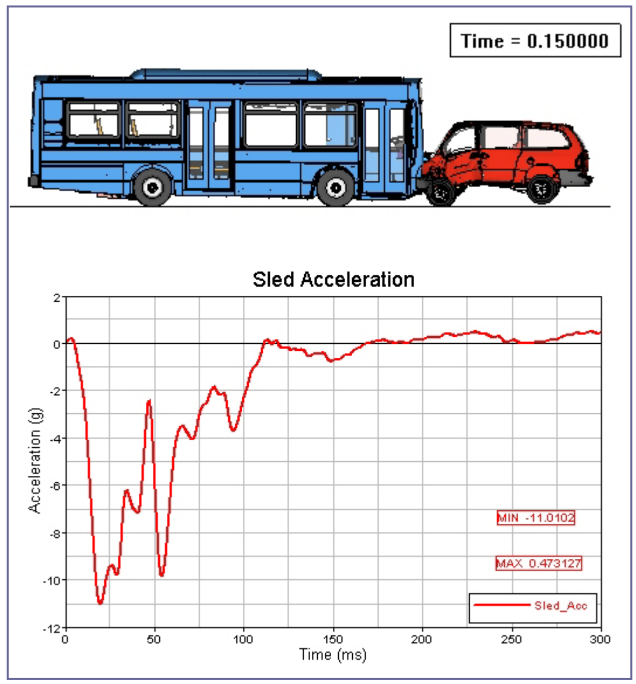

Figure 5. Crash Condition 30 mph Bus – 30 mph DC Head-on Collision 100% Overlap.

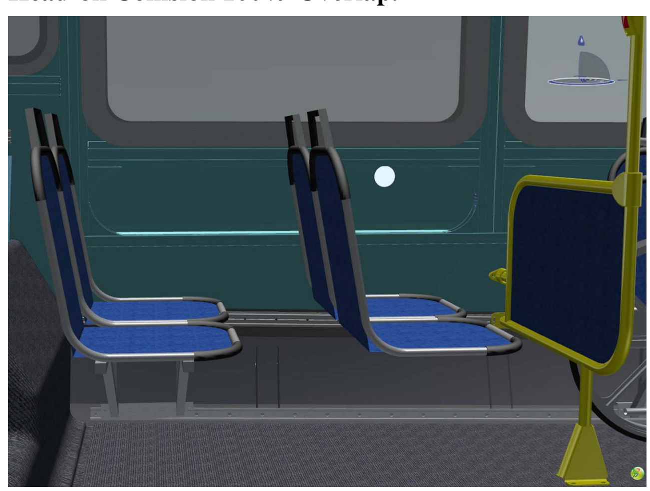

Figure 6. Seat-to-Seat Configuration (left), and Seat-to-Divider Configuration (right).

As shown in the figures 7, 8, and 9 bellow; the most common types of injury mechanisms for passengers seated in a Seat-to-Seat configuration are Neck Flexion or Extension. These injuries are due to the combination of the passengers being unrestrained and the low back seat designs. As shown in figures 7 and 10 even for the same ATD size (95th and 50th percentile in these cases) and similar setup configuration the severity of the neck flexion varies with the different seatback/head interactions; in the case shown in the left of figure 10 the neck of the ATD hits the seatback handle while for the second test the chin of the ATD hits the seatback handle. In order to reduce the severity of the injuries the design of the seatbacks needs to be improved by applying compartmentalization principles.

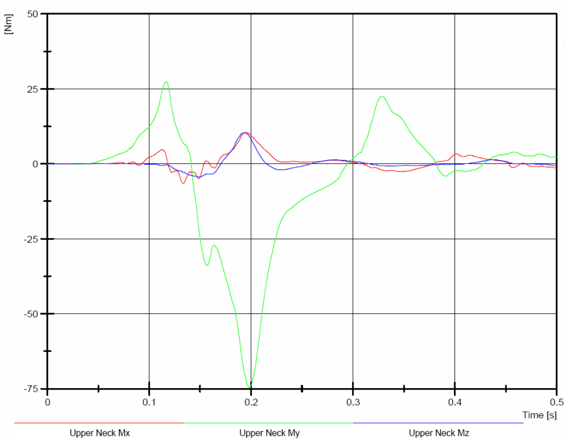

Figure 7. Sample Upper Neck Channel 50th percentile ATD Seat-to-Seat Configuration Frontal Sled Test

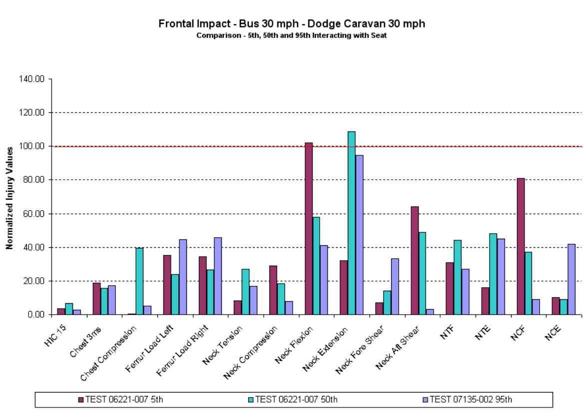

Figure 8. Bus to DC 30 mph Head-on Frontal Impact, FMVSS 208 Normalized Injury Values, Seat-to-Seat Configuration (5th, 50th and 95th percentile ATDs).

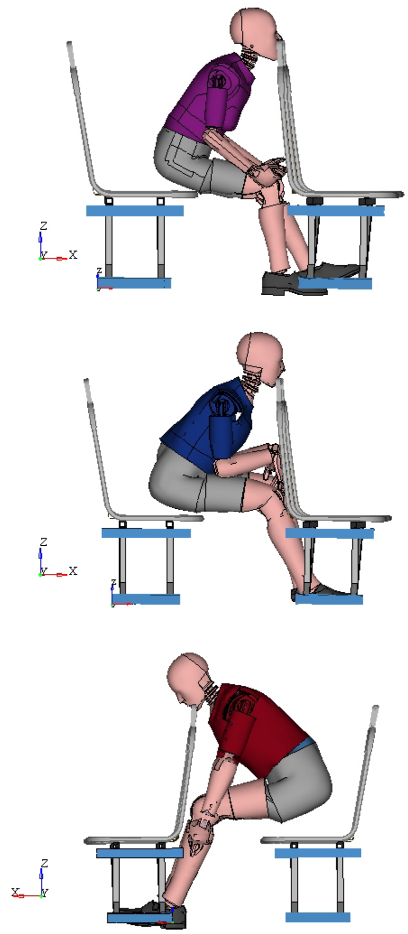

Figure 9. Example FE simulation results (5th, 50th and 95th percentile ATD) Frontal Impact Seat-to-Seat.

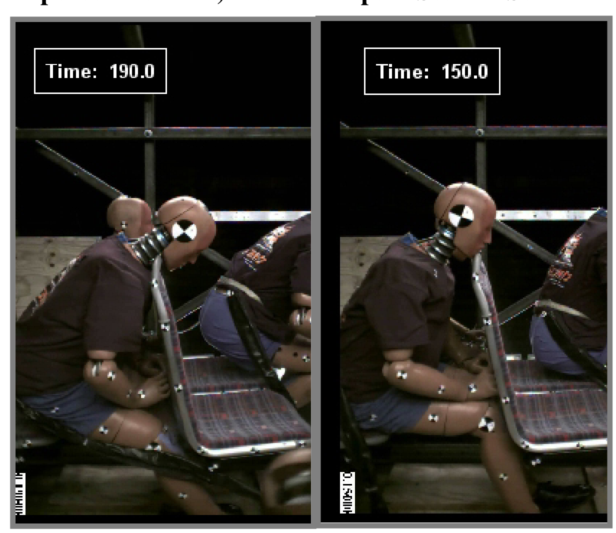

Figure 10. 95th Percentile Seat-to-Seat Configuration Frontal Sled Tests.

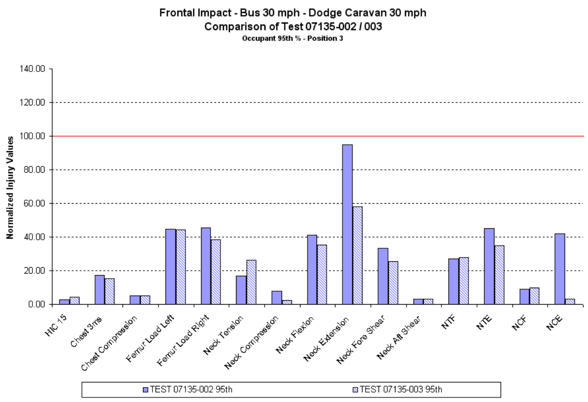

Figure 11. Bus to DC 30 mph Head-on Frontal Impact, FMVSS 208 Normalized Injury Values, Seat-to-Seat Configuration (Repeatability 95th percentile ATDs).

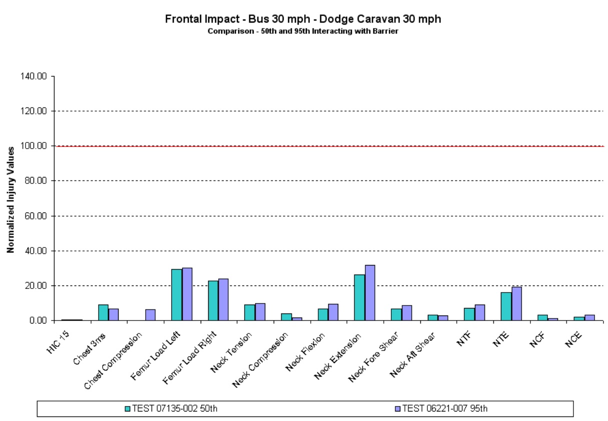

Figure 12. Bus to DC 30 mph Head-on Frontal Impact, FMVSS 208 Normalized Injury Values, Seat-to-Divider Configuration (50th and 95th percentile ATDs).

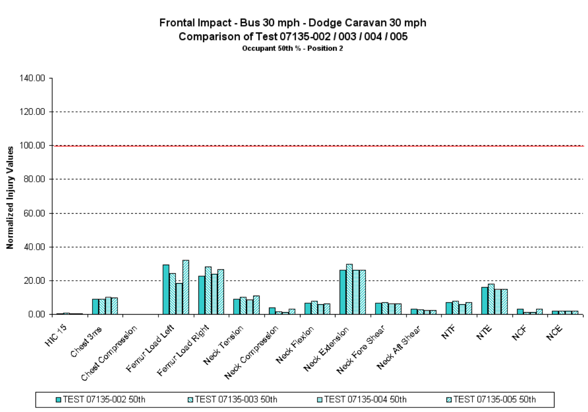

Figure 13. Bus to DC 30 mph Head-on Frontal Impact, FMVSS 208 Normalized Injury Values, Seat-to-Divider Configuration (Repeatability 95th percentile ATDs).

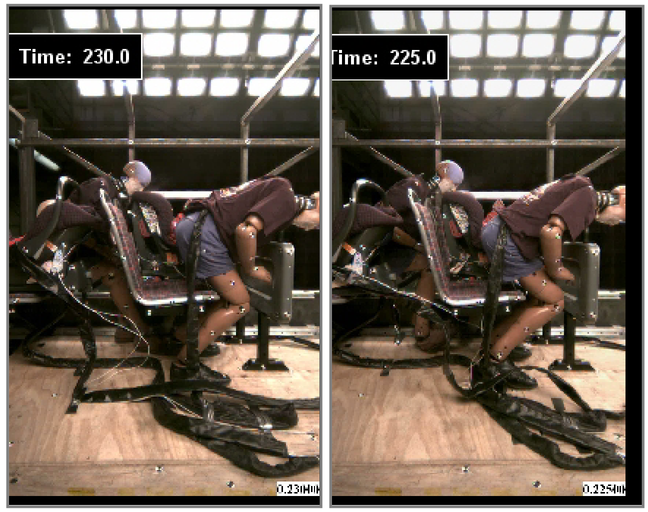

Figure 14. 95th Percentile Seat-to-Divider Configuration Frontal Sled Tests

As shown in figures 12 through 14 the normalized injury values for the Seat-to-Divider configuration are well bellow forty percent of FMVSS 208 values for both the 50 and the 95th percentile ATD.

SIDE IMPACT INJURY MECHANISMS

A series of side impact sled tests for the crash condition shown in figure 15 were conducted for occupant sizes ranging from the 5th to the 95th percentile ATDs.

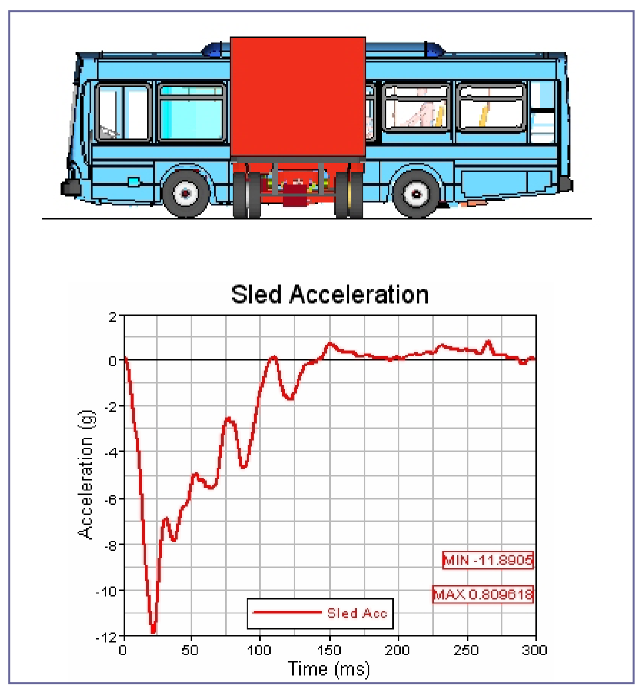

Figure 15. Crash Condition 0 mph Bus – 25 mph F800 Side Impact 90 degrees.

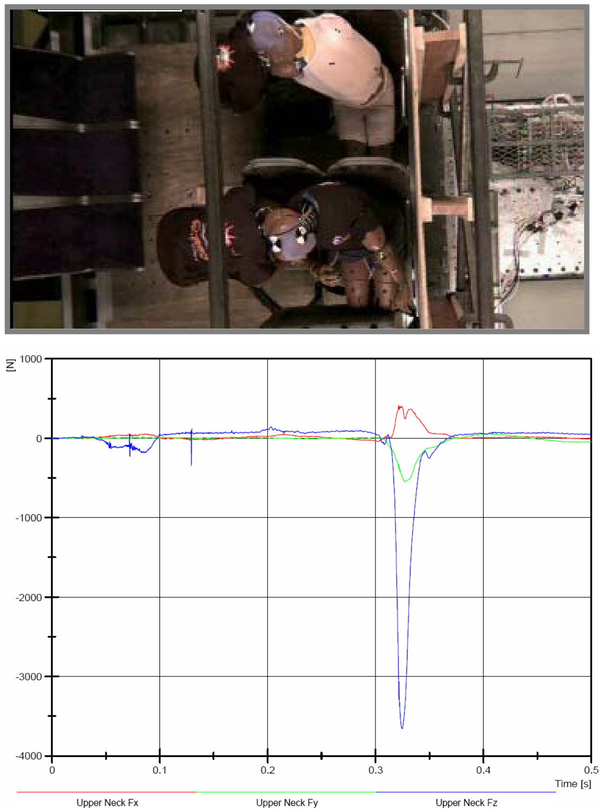

Figure 16. 5th percentile Neck Compression Injury Mechanism, due to Head-to-Head Contact.

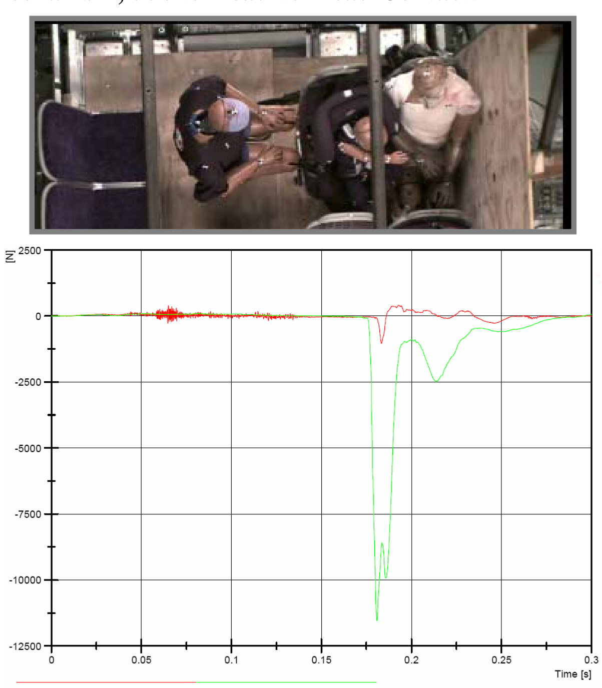

Figure 17. 95th percentile Femur Compression Injury Mechanism, due to Head-to-Head Contact.

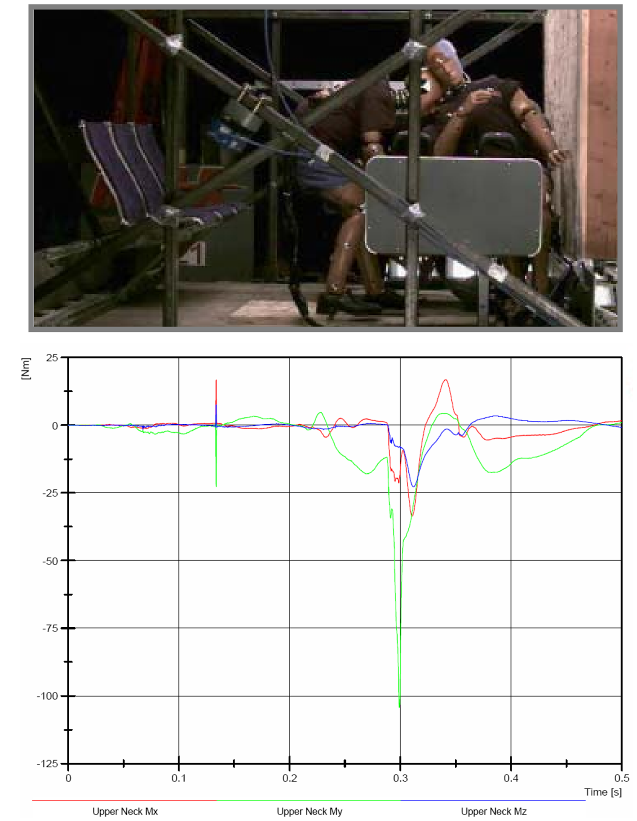

Figure 18. 50th percentile Neck Extension Injury Mechanism, due to Head-to-Head Contact.

The most common injury mechanisms for passengers seated on side facing seats during sided impact conditions are; head and neck injuries due to head-to-head or head-to-body contacts (see figures 16, and 18) and femur compression due to femur-seat contacts (see figures 18 and 19).

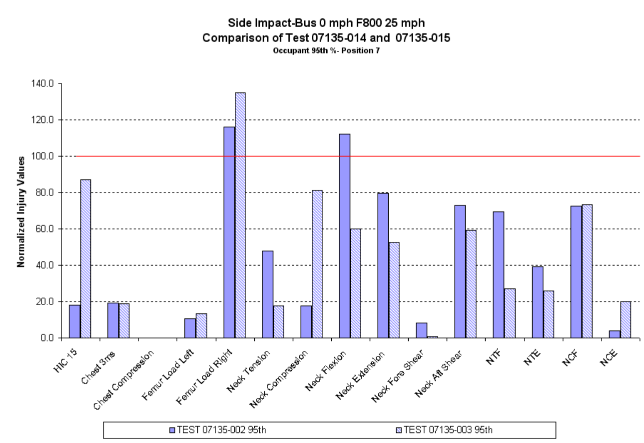

Figure 19. Bus 0 mph Bus – 25 mph F800 Side Impact 90 degrees (Repeatability 95th percentile ATDs).

REAR IMPACT INJURY MECHANISMS

A series of sled tests for rear impact configuration were conducted for occupant sizes ranging from the 5th to the 95th percentile ATDs.

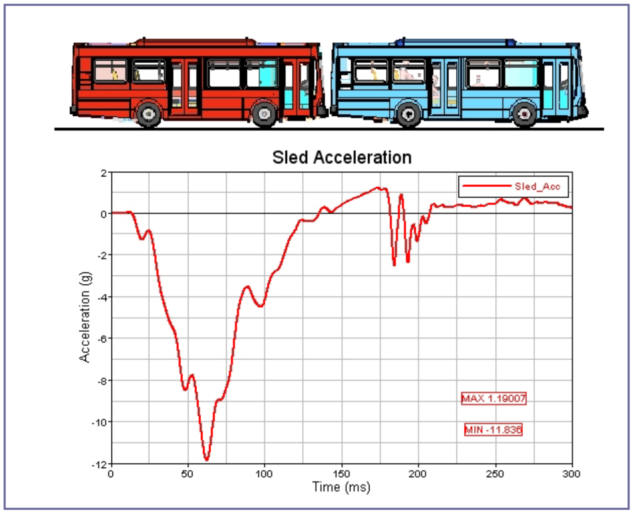

Figure 20. Crash Condition 20 mph Bus – 0 mph Bus Rear Impact

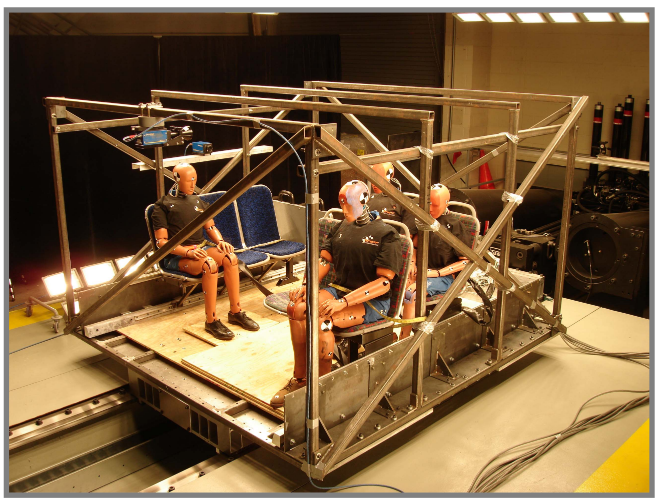

Figure 21. Crash Condition 20 mph Bus – 0 mph Bus Rear Impact

As shown in figures 24 the most common injury mechanism for occupants of all sizes (5th, 50th and 95th percentile) is neck extension. This injury mechanism is due to the low back seat designs and the rearward rotational stiffness of seatbacks. Current ongoing research at NIAR with modified high seat back designs has shown that the neck flexion moment can be significantly reduced to levels within FMVSS 208 due care values.

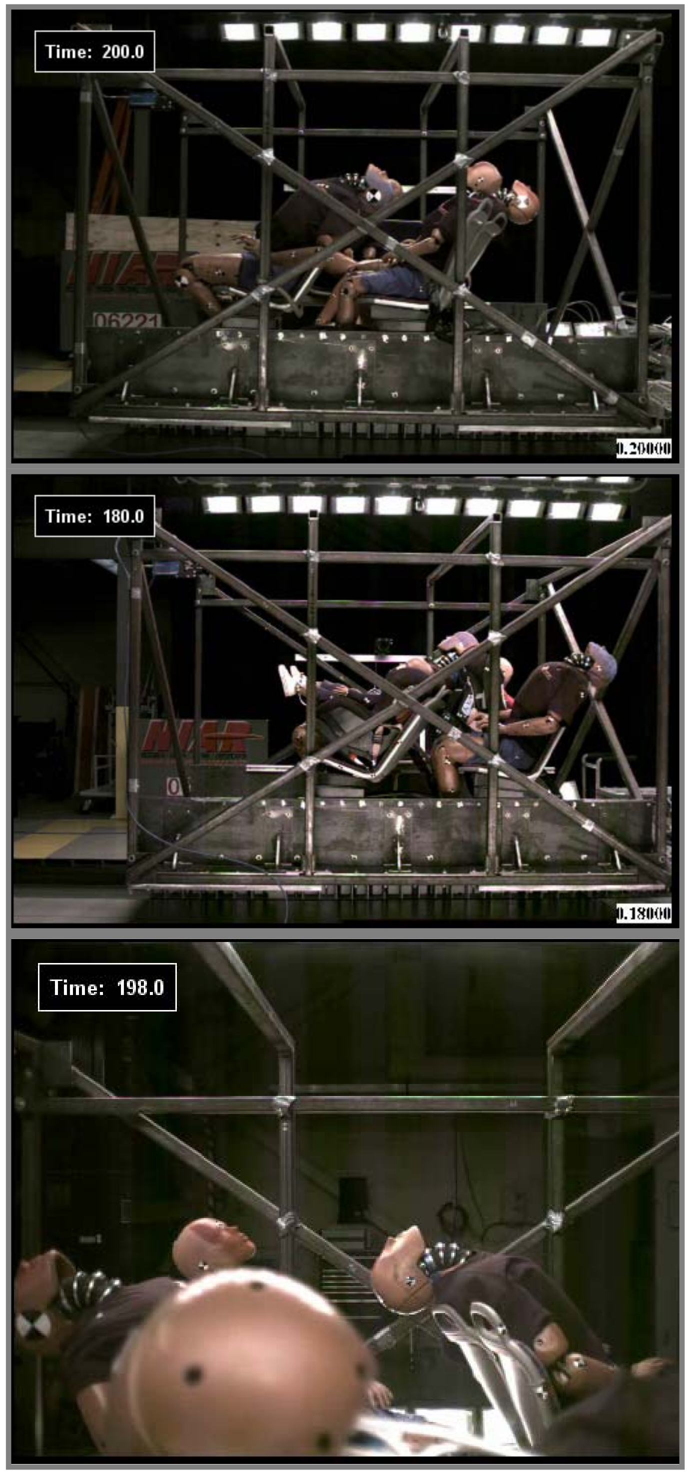

Figure 22. Crash Condition 20 mph Bus – 0 mph Bus Rear Impact (5th, 50th and 95th percentile Passenger Kinematics).

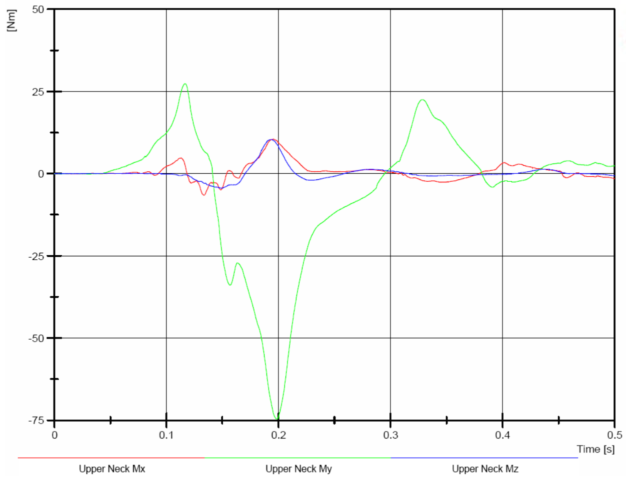

Figure 23. Crash Condition 20 mph Bus – 0 mph Bus Rear Impact (5th, 50th and 95th percentile Passenger Kinematics).

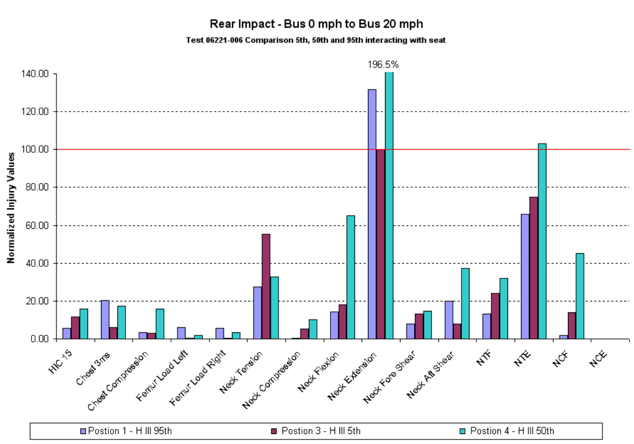

Figure 24. Bus 20 mph to Bus 0 Rear Impact Normalized Injury Values (5th, 50th and 95th percentile ATDs).

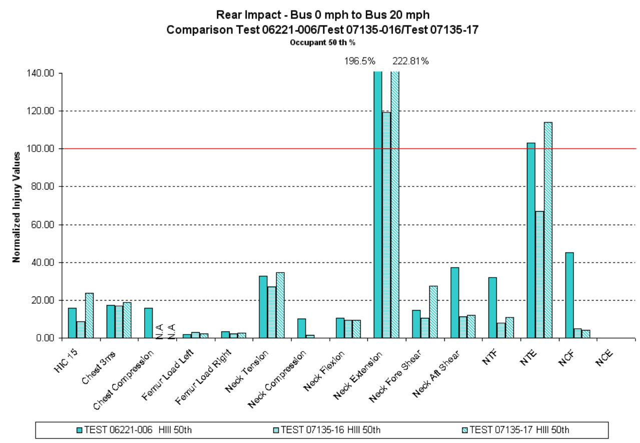

Figure 25. Bus 20 mph to Bus 0 Rear Impact Normalized Injury Values (Repeatability 50th percentile ATDs).

CONCLUSION

Buses are one of the safest forms of transportation. Nonetheless, bus crashes resulting in occupant injuries and fatalities do occur. According to the Traffic Safety Facts reports from 1999-2003, an average of 40 fatalities and 18,430 injuries of bus occupants occurred per year. The objectives of this research are to characterize the kinematics and injury mechanisms of bus passengers during typical frontal, side and rear impact conditions. Accident data from the traffic Safety Fact Reports, Buses Involved in Fatal Accidents Report and Transit Agency data were review to define typical crash scenarios. A detailed finite element model of a low floor transit bus was used to calculate the crash pulses at the passenger compartment for typical frontal, side and rear impact conditions. A series of sled tests with 5th, 50th and 95th percentile occupants were conducted at NIAR's Crash Dynamics Laboratory in order to study the occupant kinematics and to identify injury mechanisms to bus passengers.

The results of this study show that the most common injury mechanisms to bus passengers are head (HIC) and neck injury (neck extension, flexion and compression) mechanisms. The causes of these injury mechanisms are the following:

- For frontal impact conditions are due to head-seat back contacts. It should be noted that with current seatback designs it is difficult to maintain a consistent injury level, the interaction of the unbelted passenger with the seat yields either neck flexion or extension issues depending on the

- contact area. A compartmentalization approach should be used in order to provide head compliant surfaces for a wide range of passenger sizes.
- For passengers seated in side facing seats the most common injury mechanisms are head-neck injuries due to body-body contact and femur compression due to the passenger contact with seats across de aisle. These injuries could be improved if forward facing seats are used instead of side-facing configurations
- For rear impact conditions the most common injury type is neck extension. This injury mechanism is due to the low back seat designs and the rearward rotational stiffness of seatbacks. Current ongoing research at NIAR with modified high seat back designs has shown that the neck flexion moment can be significantly reduced to levels within FMVSS 208 due care values.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Anon., Standard Bus Procurement Guidelines – 30-foot Low-floor Diesel Buses, American Public Transportation Association, 2002.

[2] Olivares, G., Herman T., "Mass Transit Crashworthiness Statistical Data Analysis", NIAR Technical Report No. FTA-0002, http://www.fta.dot.gov/documents/Crashworthiness_Report.pdf, December 2005.

[3] Anon., Traffic Safety Facts 1999: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System, National Highway Traffic Safety Administration, National Center for Statistics and Analysis, U.S. Department of Transportation, Washington DC 20590. December 2000.

[4] A. Matteson, D. Blower, D. Hershberger and J. Woodrooffe, Buses Involved in Fatal Accidents Factbook 2001, Center for National Truck and Bus Statistics, University of Michigan Transportation Research Institute, Ann Arbor, Michigan, 48109-2150, February 2005.

[5] Olivares, G., "Transit Bus Crashworthiness: Finite Element Modeling and Validation", International Crashworthiness Conference, Athens, Greece, July 4-7, 2006.

[6] Olivares, G., Yadav V., "Structural Crashworthiness of Mass Transit Buses During Frontal Collisions." International Crashworthiness Conference, Tokyo, Japan, July 2008.

[7] Olivares, G., Yadav V., "Mass Transit Bus Compatibility during Frontal and Rear Collisions." ESV Paper 07-487, Lyon, France, July 2007.

ANALYSIS OF COACHES ROWS SEATS DISTANCE INFLUENCE ON THE PASSENGERS COMFORT AND SAFETY

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ABSTRACT.

Rows seats distance is a key parameter for the comfort on coaches. This distance it is also important for the passenger safety and also for example to extend the use of rearward facing CRS in a safer way. This study analyses what could be the minimum distance (based on comfort from volunteer) and how this comfort distance is affecting the passengers level of protection in R80 frontal impact with respect the minimum distance requested in current Regulations R36/R107. Volunteer testing have been performed to obtain the comfort sitting positions for coach seats geometry. Also CAE software has been used to determine minimum row seats comfort distance for a wider sample of seats geometry. In later phase, R80 sleds tests with two and four Hybrid-III dummies and with two types of seats (2-point and 3-point safety belts) have been performed, to asses the level of protection of the passengers in frontal impact at the current R36/R107 row seats distance and with the proposed one.

This study present a recommendation for a minimum row seat distance to guarantee passengers comfort and how this distance is affecting the passengers safety in frontal impact with the injury assessment criteria of both R80 and R94 for the Hybrid-III dummy. With 3-point safety belts seats, the increment on the row seat distance is beneficial for the passengers safety, except when they are unbelted and if the design of the seat is maintained. With 2-point safety belts seats, the level of protection is similar for both distances. The R94 neck injury criteria and tibia displacement are over exceed even with the lower R80 impact speed (55 kph vs 30 kph). This study shows the status of coaches frontal impact protection levels after the 2003/20/CE Directive has been made compulsory the use of the safety belts in coaches even in the city and road travels.

INTRODUCTION - OBJECTIVES.

Nowadays, the coaches seat spacing is established in the UNECE regulations to a minimum of 680 mm for the class II and III vehicles. The tendency in the market is to maintain this distance at minimum level in order to increased the number of available passengers seats in the vehicles. Garcia and Quintana-Domeque (2007) have shows the secular growth of the height in the population of 10 European countries during last decades. This growth in the height has conducted to a situation that during last years largest number of passenger can feel uncomfortable in the coaches travels. When the seat spacing is compared with the train seat spacing the coaches are in worst situation. It could be important to maintain a high level of satisfaction in the coaches transportation in order to not start a decreasing tendency in the use of this transport method in the population.

The ergonomics study conducted have been oriented to obtain a reliable minimum seat spacing that could be evaluated as comfortable for a large sample of the population, including the tallest and shortest ones.

As seat spacing is influencing the passenger safety in frontal impact, the new proposed seat spacing distance has been evaluated in terms of passenger safety. This evaluation have been performed for the two seat spacing distances, the actual and the recommended one from the ergonomics study.

METHODS.

ERGONOMIC STUDY.

To analyze the position of comfort in coach seats, measurements were made with volunteers. The selection of volunteers is done with the aim of having the following percentiles of the population: 5^{th} female, 50^{th} male and 95^{th} male. To determine the comfort position of each percentile on a coach seat we follow the recommendations found in the literature and also through tests conducted with volunteers on a seat selected mounting on a platform. Output form these volunteers have been used to obtain the minimum distance between seats in the module test and the maximum angle of inclination of front back until volunteer leg contact. These parameters measured in the laboratory have been used to perform an analysis with the selected software ergonomics (CATIAv5).

In a latter process, different parameters have been considered to extend the evaluation of comfort to a wider sample of seats coaches using the CAD software, these are:

- Seat back dimensions and angle.
- Sitting angles.
- Armrest.
- Height, deep, wide and surface of the cushion.
- H point height (closely to popliteus muscle).
- Free space for lower legs.

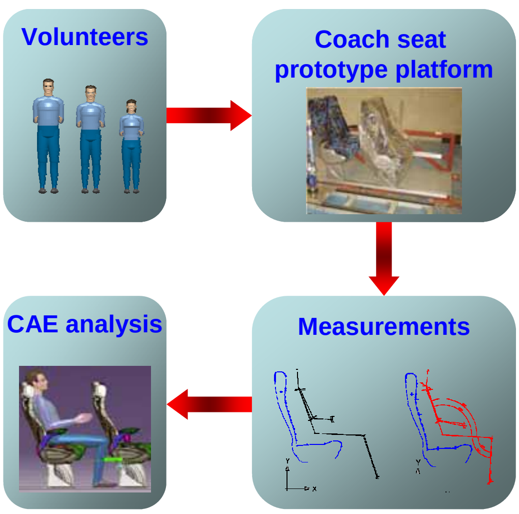


Figure 1. Ergonomic study methodology.

SAFETY STUDY.

For the safety study there were conducted a total of 12 sled tests. These tests have been performed as specified by the ECE R80 (i.e. 30-32 kph with a mean deceleration between 6.5 – 8.5 g). Six tests were performed at a short distance (the minimum distance required by the ECE R36 - 680 mm) and the others to a greater distance (obtained through the ergonomic study). It has also tested different configurations (restraint systems and seat occupancy). Both seat belts with 2 points and three points have been tested. Three scenarios-configurations have been identified to perform the tests (two of them taken from the ECE R80), these settings are:

- **Setup 1:** Safety belts fastened (two rows of seats with four dummies). *Objective:* asses rear passengers safety when forward seat if loaded/deformed by its own passengers. This is considered the most realistic configuration.
- **Setup 2:** No belts fastened (from ECE R80 – Test 1). *Objective:* asses form seat restraint performance.
- **Setup 3:** Safety belts fastened (from ECE R80 – Test 2). *Objective:* asses passengers impact against a free front seat.

As shown above, the latter two configurations correspond to regulatory tests (ECE R80), while the first configuration corresponds to a real situation.

Seat Belt	Distance	Setup 1 	Setup 2 	Setup 3 
2P	680 mm	X	X	X
	Ergonomic	X	X	X
3P	680 mm	X	X	X
	Ergonomic	x	X	X

Figure 2. Sled tests setup configuration.

Each sled test was conducted with two high speed cameras (one on each side) with a sampling rate of 1000 fps. In addition, the contacts in the back of the seats have been checked (using the same colour code as in EuroNCAP frontal impact).

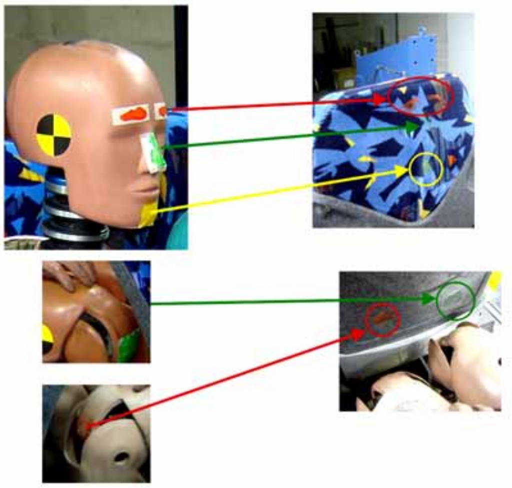


Figure 3. Colour codes for checking the contacts.

This methodology allows for a comparative analysis between the different distances between seats tested (main objective of the study), different scenarios selected (for the same restraint system and distance) and the different safety belts configuration (for the same scenario and distance).

Below is the nomenclature used in the tests, in order to clarify the different images or graphs shown later.

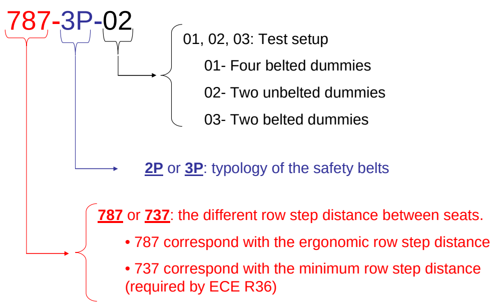


Figure 4. Nomenclature used in the sled tests.

To analyze the results, four Hybrid III 50th male dummies have been used with the following instrumentation:

Dummy Hybrid III 50th			
Dummy part	**Instrumentation**	**Direction**	**Dummy**
Head	3 axis accelerometer	Ax Ay Az	LD / RD
Neck	Upper neck load cell	Fx Fy Fz	- / RD
		Mx My Mz	- / RD
Thorax	3 axis accelerometer	Ax Ay Az	LD / RD
	Displacement	Dx	LD / RD
Pelvis	3 one axis accelerometer	Ax Ay Az	LD / RD
Right femur	Load cell	Fz	LD / RD
Left Femur	Load cell	Fz	LD / RD
Right tibia upper	Displacement	Dx	LD / RD
Left tibia upper	Displacement	Dx	LD / RD
LD = Right dummy. RD = Left dummy			

Figure 5. Instrumentation used in the sled tests.

The degree of safety of the seats has been checked after running the tests. This would have taken the criteria of ECE R80. Since the ECE R80 have a shorter injury criteria assessment than a more recent ones regulations, it was decided to increment the aim of the study introducing the criteria imposed by ECE R94. Below, there is a table with the analysed requirements:

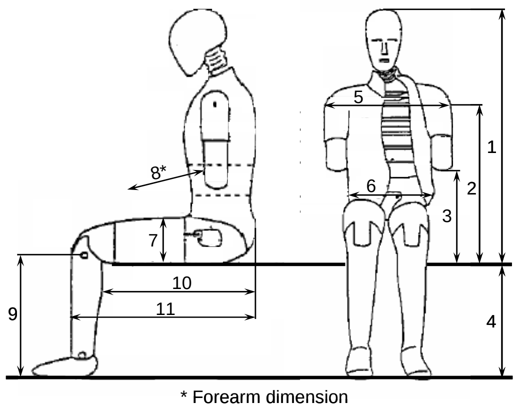
	Criterion		Reglamentation
Head	Head injury criterian (HIC_{36ms})		ECE R80
	Head resultant acceleration (3ms)		ECE R94
Neck	Neck injury criteria (NIC)	Axial force	ECE R94
		Shear force	ECE R94
		Extension moment	ECE R94
Thorax	Thorax compression criterion (ThCC)		ECE R94
	Thorax resultant acceleration		ECE R80
	Viscous criterion (V*C)		ECE R94
Leg	Femur compression force		ECE R80
	Movement of the sliding knee joints		ECE R94

Figure 6. Injury criteria analysed.

RESULTS.

ERGOMOMIC STUDY.

For the ergonomic study has been used a total of nine volunteers (three for each percentile). To check if the sample is representative, it have been taken some external measurements for each of the percentiles in a 90 degrees backrest chair. The following figure shows the dimensions taken of the volunteers:



	Group 1: 5th Female			Group 2: 50th Male			Group 3: 95th Male		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	804	840	775	888	918	903	952	974	918
2	560	595	520	650	648	640	670	700	670
3	235	245	200	250	240	220	235	270	235
4	415	405	410	440	460	490	500	510	510
5	369	363	384	439	444	450	456	425	471
6	363	379	359	333	355	365	396	384	427
7	121	125	112	160	137	145	135	140	155
8	230	240	230	290	310	290	300	295	310
9	445	450	445	515	525	540	560	560	550
10	460	468	466	530	560	505	545	567	564
11	550	580	565	635	665	640	655	685	701
A	1530	1570	1500	1760	1800	1770	1840	1910	1850
B	48	55	50	80	88	80	80	83	95
	A: Total height. B: Total mass (kg). Dimenssions in "mm".								

Figure 7. Volunteer measurements.

Once the general measures for each volunteer is done, the volunteer was sited in a real seat coach (unaccompanied) and remains for at least 20 minutes. When the volunteer is comfortable enough, a number of representative points are taken in order to obtain a stickman of the volunteer. These points are taken from Appendix K of UMTRI report. Each measuring point was taken with a three-dimensional measuring machine (FARO-Arm®). Below there is an example of the measurement points taken as reference (Figure 8) and the measurement of a volunteer about his seat (Figure 9).

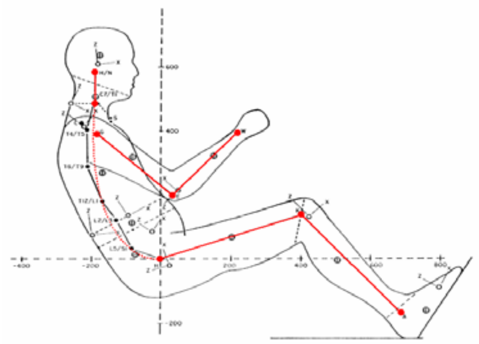


Figure 8. Reference points.

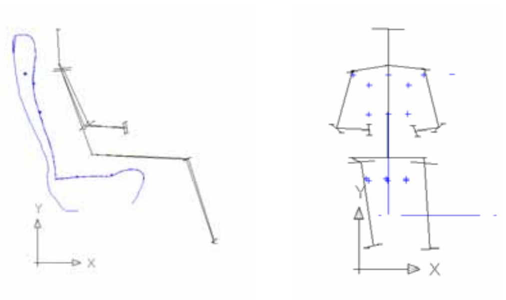


Figure 9. Example of the measurements taken.

Once the volunteers got their position of comfort and measurements made with the FARO-Arm®, the forward seat was moved until the volunteer ceases to be in a comfortable position (measurement the step between rows of seats). With this distance between seats, the backrest (of the front seat) was reclined until the volunteer got another uncomfortable position. The measures of the step between seats and the back tilt are shown below:

		Distance L (mm)	Distance H (mm)
Group 1 5^{th} Female	Volunteer 1	780	723
	Volunteer 2	825	768
	Volunteer 3	770	713
Group 2 50^{th} Male	Volunteer 4	680	623
	Volunteer 5	740	687
	Volunteer 6	785	728
Group 3 95^{th} Male	Volunteer 7	670	613
	Volunteer 8	635	578
	Volunteer 9	605	548

Figure 10. ***Distance L:*** **step of rows.** ***Distance H:*** **internal distance between backseats.**

		Angle α (º)	Contact
Group 1 5^{th} Female	Volunteer 1	60.5	Rear seatback tray
	Volunteer 2	55.5	Seatback
	Volunteer 3	57.0	Seatback
Group 2 50^{th} Male	Volunteer 4	69.6	Seatback
	Volunteer 5	58.7	Seatback
	Volunteer 6	54.7*	Maximum reclined
Group 3 95^{th} Male	Volunteer 7	54.7*	Maximum reclined
	Volunteer 8	68	Upright position
	Volunteer 9	58.1	Seatback

Figure 11. Seatback angles.

Two types of ergonomic position were obtained for each group percentile representing by the volunteers selected. One more upright (back support on the backrest of the seat), while the other is lying stretching the legs. These measurements can be seen in Figure 9.

In the literature, there were no comfort parameters for coach passengers, perhaps the closest comfort position is the driving position in coaches. This ergonomic position is defined in Figure 12. The five angles defined along with anthropometric measurements taken (see Figure 7) uniquely define the volunteer.

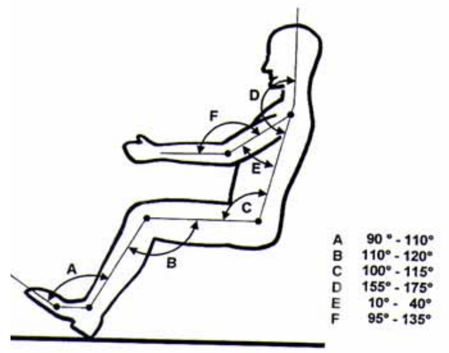


Figure 12. Position of comfort for coach drivers (Kraus - 2003)

In the case of the angles defined in the legs (back - femur / femur - tibia) the average of the two angles has been taken. These angles can be seen in the figure below.

		Tibia - Foot A	Femur - Tibia B	Back - Femur C	Back - Neck D	Back - Vertical D'
Group 1 5^{th} Female	Volunteer 1	102	122	137	159	26
	Volunteer 2	70	84	122	167	18
	Volunteer 3	91	104	126	160	23
Group 2 50^{th} Male	Volunteer 4	85	92	114	159	18
	Volunteer 5	83	85	115	170	25
	Volunteer 6	118	127	120	154	20
Group 3 95^{th} Male	Volunteer 7	91	87	105	149	20
	Volunteer 8	109	111	113	162	20
	Volunteer 9	88	91	113	154	20

Figure 13. Angles of the comfortable position.

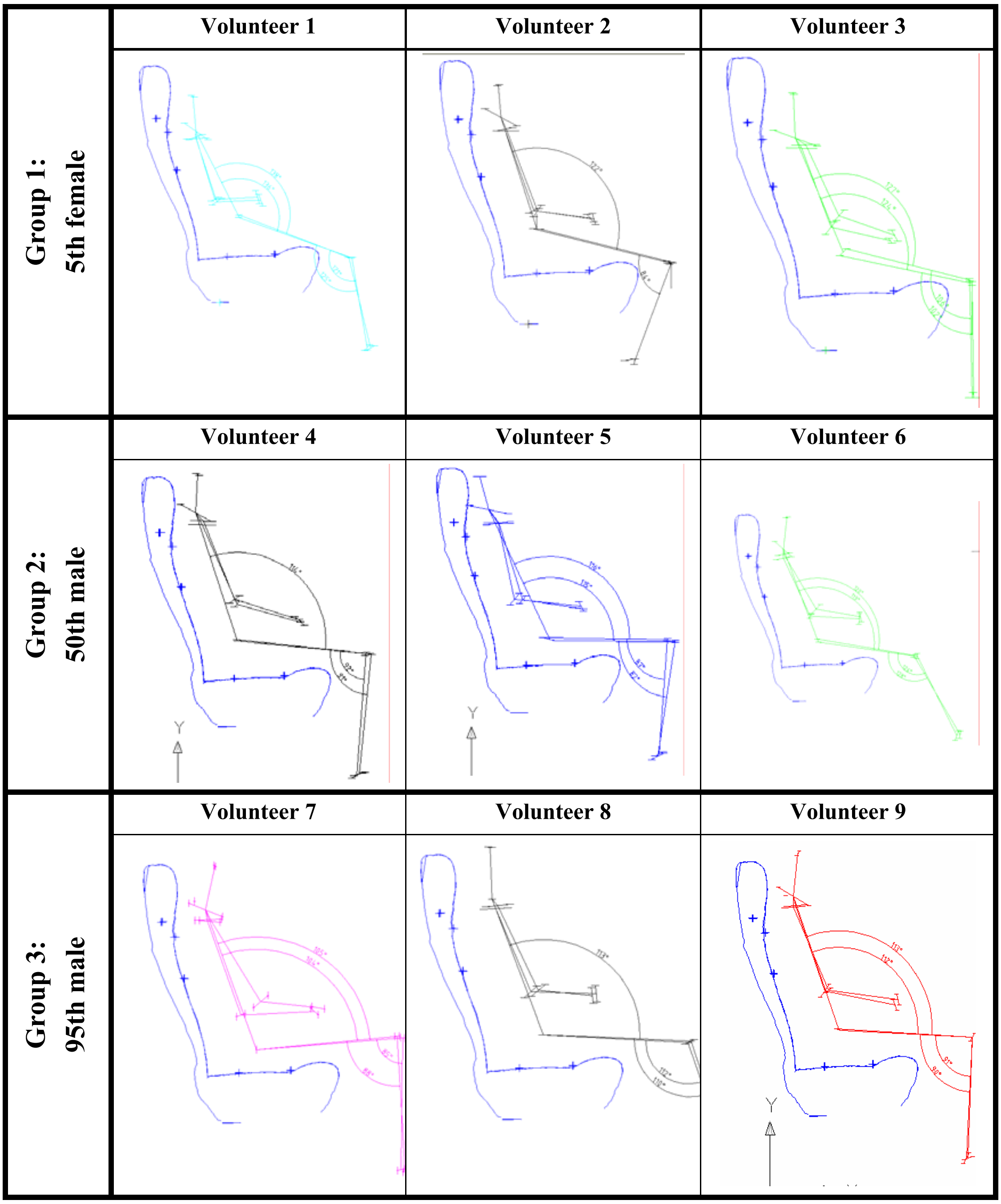


Figure 14. Measurements taken from the volunteers.

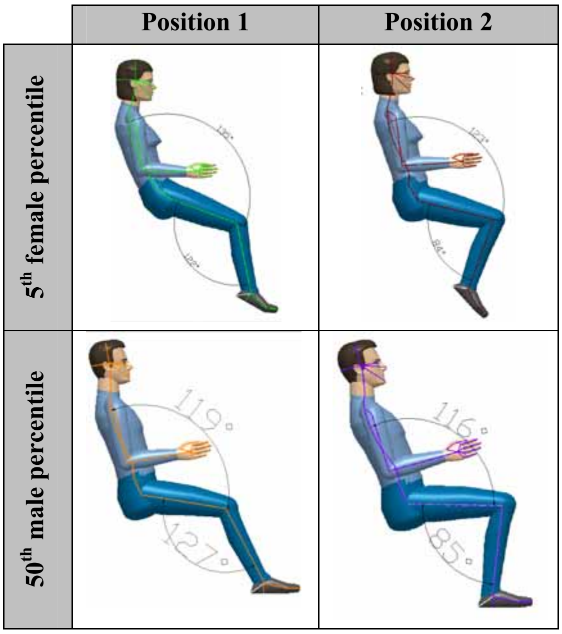
Comparing the angles measured in the volunteers with those defined as angles of comfort it is obtained that:

- The values of the 'A' angle (tibia to foot) is located between 70º and 118º, but the largest number of respondents is around the 85-90º. This range is higher than the reference, however, this is because the volunteers support the foot in a horizontal plane, while the reference is set for a driver that support their foot on a pedal.
- The 'B' (femur to tibia) values are between 84º and 127º. Here the two

trends mentioned above are shown. The more upright position obtained 'B' angle values of 84-92º, while the reclining position is at values around 105º to 125º (similar to the reference position).

- The 'C' (back to femur) values lie between 105 and 137º. It is noted that for the smallest volunteers (5th female) got angles much greater than in other volunteers. This is caused by the height of the chair, in which the small volunteers were able to recline their back in order to rest their foot on floor. For other volunteers, got values between 105º to 120º, close to the reference.
- The 'D' (back to neck) values are between 149º and 170º. Only one volunteer is outside the reference range (155º-175º), by 6º.

These data have been entered into the ergonomic module of CATIAv5. Since it has been proven that there are two tendencies in the positions for each percentile, these two positions were analysed through the ergonomics module. Finally a total of 6 models were necessary to study (two positions for each of the percentiles).



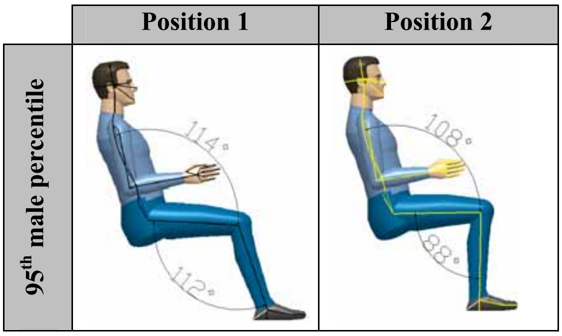


Figure 15. Different models analysed.

Once obtained the various percentiles, it is necessary to incorporate into the ergonomic model different seats for a larger and reliable study. First, the volunteers seat tested were taken as a reference and incorporate into the model, then through a market study (25 real seats were measurement), the maximum and minimum dimensions of the seats had been obtained. These measurements are shown bellow:

	Seat test	Maximum	Minimum
Total heigh (mm)	1128	1044	1153
Seatback angle (º)	22	18	25
H point (mm)	503	470	520
Length pad (mm)	468	430	490
Seat/pad heigh (mm)	465	425	495

Figure 16. Seat dimensions.

Once entered into the model the percentile, their comfort position and the seats, a simulation matrix is defined in order to perform different virtual checks. The distance between seats and backrest inclination were varied into the model. Figure 17 shows the matrix of the performed simulations.

		5th female	50th male	95th male
Upright position of seatbacks	Seat test	X	X	X
	Maximum	X	X	X
	Minimum	X	X	X
Reclined of the front seatback	Seat test	X	X	X
	Maximum	X	X	X
	Minimum	X	X	X
Reclined of both seatbacks		X	X	X

Figure 17. Simulation matrix.

SAFETY STUDY.

A total of 12 sled tests were being performed as described above. Six of these tests have been conducted with the minimum distance between seats required by regulation (680 mm) which corresponds with a passage between seats of 737 mm. The other six tests were performed with the ergonomic distance (mentioned later in this article), which corresponds to a distance between seats of 730 mm (for the tested seat it was a row step distance of 787 mm).

Each of the registered signals have been filtered according to the requirements imposed by regulation (ECE R80, ECE R94 or SAE J211, depending on the criterion to be evaluated). For the analysis of results, the most important data of each test have been taken into account, and the signs that do not coincide with the direction of impact were not taken into account. The following figure shows the signals that have been taken for analysis:

Body part	Signal
Head	Resultant head acceleration
Neck	Upper neck force X (+)
	Upper neck force Z (Tension)
	Upper neck moment Y (Extension)
Thorax	Resultant thorax acceleration
	Thorax deflection
Pelvis	Resultant pelvis acceleration
Femur	Right femur force Z (Compression)
	Left femur force Z (Compression)
Knee	Right knee slider
	Left knee slider

Figure 18. Signals used for the result analysis.

Below is shown a comparison of each of the scenarios tested (shown in Figure 2) with equal restraint system and varying the row step distance. A comparison of the kinematics of the tests (at 0, 50, 100 and 150 ms after the start of the test) and the maximum values of recorded signals were done.

Setup 1 – <u>3 point seat belt.</u>

The sequence of images shows that the rear ones dummies do not impact with the head against the back seat (regardless of distance). This fact is due to the deformation of the seat back caused by the front dummies through the third point of the safety belt. In both distances, the knees impact against the front seat, while the long distance contact is much lower (as it can be seen in the compression load of the femur - Figure 20).

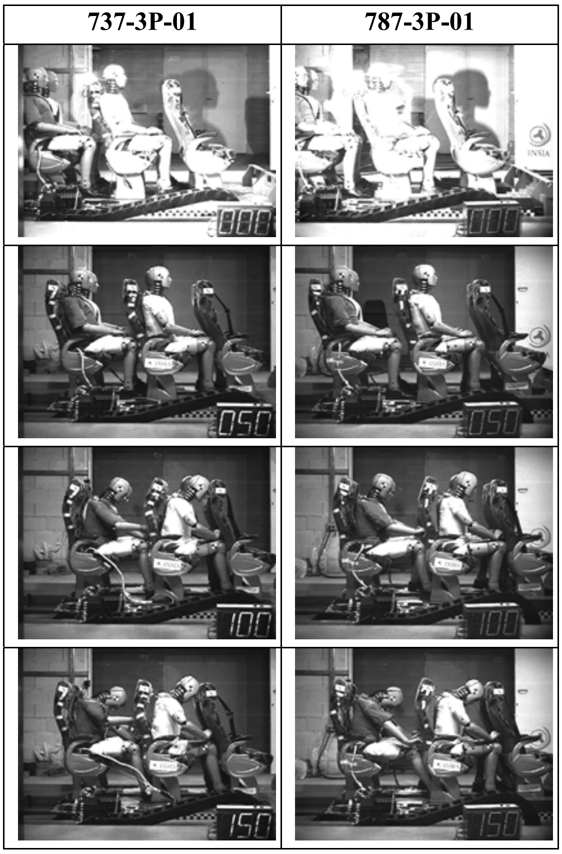


Figure 19. Sequence of images for setup 1 (3P seat belt).

	737-3P-01		787-3P-01	
Signal	Rear left	Rear right	Rear left	Rear right
Head AcRes (g)	34.38	33.57	27.11	26.53
UpNeck Fx (N)	-	99.12	-	73.89
UpNeck Fz (N)	-	1177.82	-	897.06
UpNeck My (N·m)	-	-12.24	-	-13.15
Thorax AcRes (g)	18.24	17.84	18.31	17.61
Thorax Def (mm)	-5.85	-10.99	-9.91	-17.66
Pelvis AcRes (g)	27.22	27.88	19.35	19.41
Right Femur Fz (N)	-1348.13	-1251.8	-890.82	-169.37
Left Femur Fz (N)	-1016.16	-1303.12	-154.28	-1040.62
Right Knee Slider (mm)	8.88	3.53	4.7	0.33
Left Knee Slider (mm)	4.28	7.9	0.1	5.36

Figure 20. Signals comparison (Setup 1 – 3P).

Setup 2 – <u>3 point seat belt.</u>

In this configuration, the occupants were not using the restraint system. In the first moments there was a free movement of occupants until impact with the knees (Figure 21). After this, there was a rotation of the body head, neck and shoulders contact with the front seat back. In long distance configuration, the relative velocity of impact is greater, so the values recorded in the head, neck and femur are greater, with increased values at around 15-20%, sometimes reaching 30% (Figure 22).

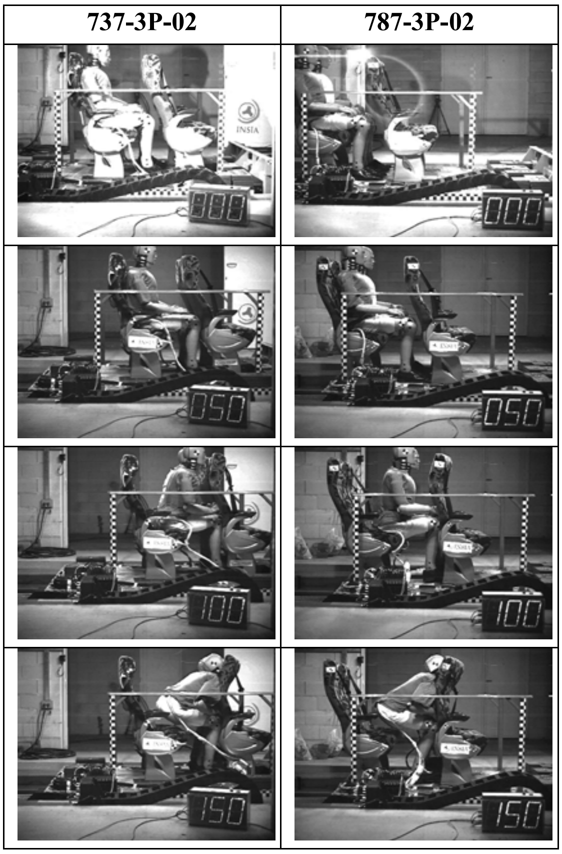


Figure 21. Sequence of images for setup 2 (3P seat belt).

	737-3P-02		787-3P-02	
Signal	**Rear left**	**Rear right**	**Rear left**	**Rear right**
Head AcRes (g)	89.57	87.2	102.45	107.14
UpNeck Fx (N)	-	1824.4	-	1456.26
UpNeck Fz (N)	-	1791.15	-	2118.25
UpNeck My (N·m)	-	-29.13	-	-46.53
Thorax AcRes (g)	18.41	19.19	21.61	21.74
Thorax Def (mm)	-2.48	-2.25	-0.08	-0.94
Pelvis AcRes (g)	25.44	25.77	32.88	34.66
Right Femur Fz (N)	-3165.13	-3872.17	-3615.07	-4209.79
Left Femur Fz (N)	-3790.15	-3306.67	-5249.11	-4529.61
Right Knee Slider (mm)	14.05	10.81	13.54	14.13
Left Knee Slider (mm)	11.72	13.62	13.31	15.09

Figure 22. Signals comparison (Setup 2 – 3P).

Setup 3 – 3 point seat belt.

In this configuration, two occupants used the restraint system (in this case the 3-point belt). It is noted that in both distances the knees impacted against the front seat back. Also occurs with the head (because the front seat did not have an occupant and it was not deformed through the 3-point belt). In long distance, both contacts the head and the knee are much lower than in the short distance (with values 50% lower in the head acceleration or femur force).

Figure 24 shows that the signals of the left side dummy on the left (in the long distance test) are crossed out, this is because during the test its safety belt did not work properly and the retractor did not locked. This fact is evident in the kinematics secuence.

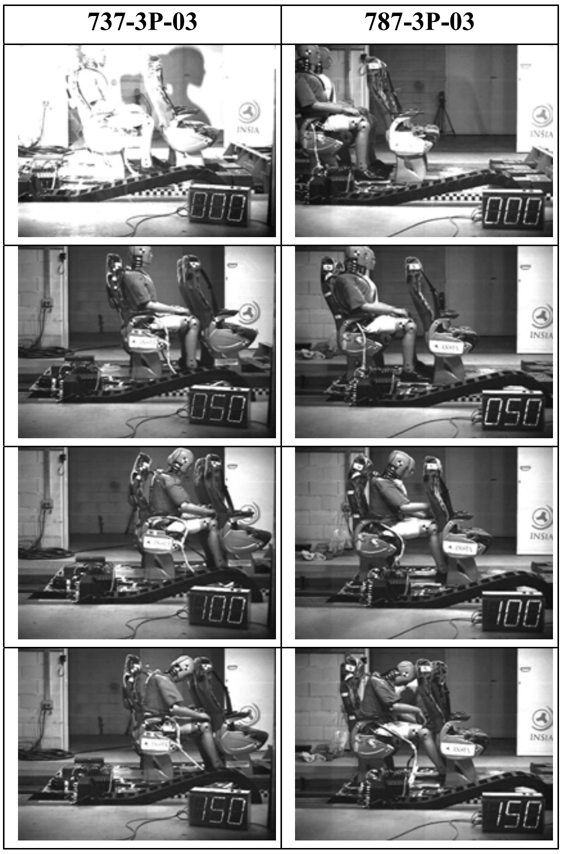


Figure 23. Sequence of images for setup 3 (3P seat belt).

	737-3P-03		787-3P-03	
Signal	**Rear left**	**Rear right**	**Rear left**	**Rear right**
Head AcRes (g)	75.64	80.95	~~101.35~~	46.3
UpNeck Fx (N)	-	90.82	-	98.24
UpNeck Fz (N)	-	1036.01	-	929.19
UpNeck My (N·m)	-	-18.13	-	-14.16
Thorax AcRes (g)	22.91	22.23	~~15.34~~	19.13
Thorax Def (mm)	-8.03	-9.42	~~-6.14~~	-9.71
Pelvis AcRes (g)	30.1	27.26	~~24.41~~	25.01
Right Femur Fz (N)	-1337.09	-1442.16	~~-1719.09~~	-577.68
Left Femur Fz (N)	-1856.47	-1488.09	~~-931.21~~	-1027.09
Right Knee Slider (mm)	9.25	5.81	~~9.8~~	3.57
Left Knee Slider (mm)	8.16	9.35	~~4.62~~	6.84

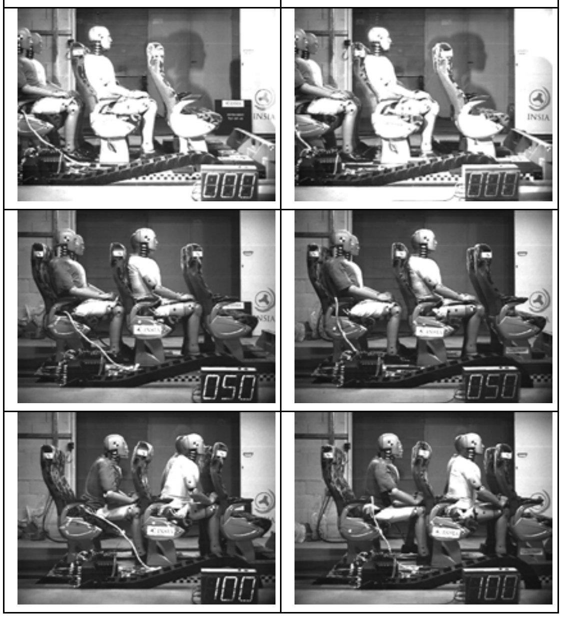
Figure 24. Signals comparison (Setup 3 – 3P).

Setup 1 – 2 point seat belt.

This test was performed with four adult Hybrid III 50th male, using the 2-point safety belt. There were no significant differences in the kinematics of the test, at the beginning a contact with the knees were occurred and then hit the head (no elevation of the pelvis due to the two-point safety belt). The values were similar in the head deceleration. The femur force registered was lower for long distance (approximately 30%).

The Figure 26 shows a knee slider displacement of one dummy was crossed out, this is because the data offered by the sensor were not reliable.

737-2P-01	787-2P-01



737-2P-01	787-2P-01

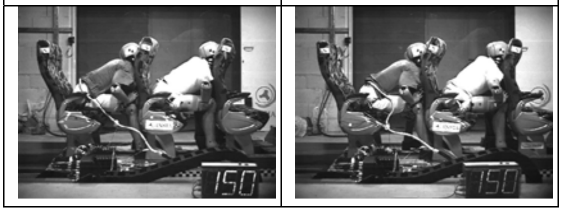


Figure 25. Sequence of images for setup 1 (2P seat belt).

	737-2P-01		787-2P-01	
Signal	**Rear left**	**Rear right**	**Rear left**	**Rear right**
Head AcRes (g)	106.15	119.04	104.79	105.92
UpNeck Fx (N)	-	893.1	-	1177.23
UpNeck Fz (N)	-	1612.26	-	1524.91
UpNeck My (N·m)	-	-98.88	-	-79.73
Thorax AcRes (g)	16.35	16.97	17.42	16.61
Thorax Def (mm)	-0.15	-0.06	-0.07	-0.09
Pelvis AcRes (g)	32.11	30.8	27.11	29.64
Right Femur Fz (N)	-1790.55	-2810.48	-1204	-1725.53
Left Femur Fz (N)	-2152.08	-1680.27	-1655.97	-1273.6
Right Knee Slider (mm)	9.74	10.26	5.65	7.9
Left Knee Slider (mm)	8.5	9.63	~~0.12~~	6.98

Figure 26. Signals comparison (Setup 1 – 2P).

Setup 2 – 2 point seat belt.

This configuration is similar to the tested seats with three points (Setup 2 – 3 point set belt). The behaviour of the seats with 2 or 3 points seat belt are different (although the same model of chair were used), this fact is due to the 3-point seat is more resistant than the 2-point seat belt. As in the configuration of three points seat belt, the highest relative speed on the dummies tested with the long distance with respect to the front seat, caused higher values in the short distance (15 to 30% higher).

The Figure 28 shows a knee slider displacement of one dummy was crossed out, this is because the data offered by the sensor were not reliable.

737-2P-02	787-2P-02

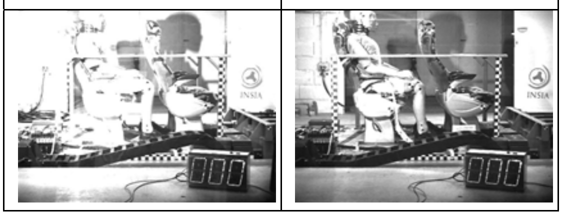


Figure 27. Sequence of images for setup 2 (2P seat belt).

	737-2P-02		787-2P-02	
Signal	Rear left	Rear right	Rear left	Rear right
Head AcRes (g)	74.55	78.82	75.33	88.23
UpNeck Fx (N)	-	1010.12	-	1197.57
UpNeck Fz (N)	-	1765.23	-	1612.48
UpNeck My (N·m)	-	-70.18	-	-78.2
Thorax AcRes (g)	16.45	15.69	15.37	16.58
Thorax Def (mm)	-2.56	-2.23	-2.31	-2.53
Pelvis AcRes (g)	26.5	25.2	26.43	29.25
Right Femur Fz (N)	-3370.93	-3327.98	-3651.98	-4624.57
Left Femur Fz (N)	-3675.63	-4016.71	-3790.17	-3856.51
Right Knee Slider (mm)	13.75	6.88	12.65	14.31
Left Knee Slider (mm)	~~19.91~~	14.35	13.72	13.83

Figure 28. Signals comparison (Setup 2 – 2P).

<u>**Setup 3** – 2 point seat belt.</u>

Finally, the configuration with two dummies fastened with two-point belt. The behaviour was similar to that of the four dummies belted with two-point safety belt. First there was a contact of the knees and finally the head impacted against the seat back. Increasing the row step distance caused a higher relative velocity of head impact and this caused higher head decelerations. Furthermore, the contacts of the knees were lowering severe in the long distance obtained smaller compression force.

Figure 29. Sequence of images for setup 3 (2P seat belt).

	737-2P-03		787-2P-03	
Signal	Rear left	Rear right	Rear left	Rear right
Head AcRes (g)	86.71	82.96	87.59	106.62
UpNeck Fx (N)	-	456.05	-	627.35
UpNeck Fz (N)	-	1707.19	-	1608.94
UpNeck My (N·m)	-	-94.07	-	-99.14
Thorax AcRes (g)	18.85	18.66	17.5	16.44
Thorax Def (mm)	-3.09	-4	-1.7	-2.2
Pelvis AcRes (g)	29.18	30	34.32	36.23
Right Femur Fz (N)	-1832.24	-3006.83	-1145.52	-2619.81
Left Femur Fz (N)	-2848.49	-2299.13	-2418.12	-2232.04
Right Knee Slider (mm)	10.04	11.68	7.69	10.97
Left Knee Slider (mm)	11.11	11	11.26	10.12

Figure 30. Signals comparison (Setup 3 – 2P).

DISCUSSION.

<u>ERGONOMIC STUDY.</u>

When the matrix of CAE simulations, shown in Figure 17, were done, a comfortable distance were obtained form an ergonomic point of view. An example of these simulations is shown in the figure below:

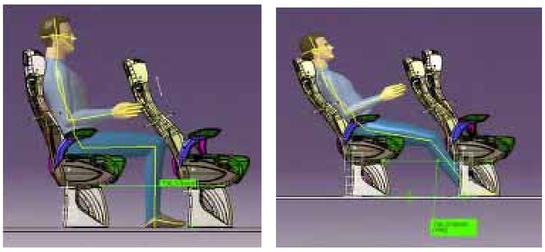


Figure 31. CAE análisis.

Authors define *"Distance L"* as the row step distance (measuring the same point between two adjacent rows of seats) and *"Distance H"* as the distance between seats (measured at the front of the rear seat and the back of the front seat - ECE R36 – *seat spacing*). For the seat included in the model, the difference between the *"Distance L"* and the *seat spacing* was 57 mm, therefore to obtain the distance between seats (*"Distance H"*) only need to subtract 57 mm from the values given in Figure 32 and Figure 33.

In configurations that did not recline the back (reasonable situation to not increase too much the row step distance between seats), the following results were obtained:

			Seat test	Maximum	Minimum
Distance L	Group 1 5th Female	Pos 1	592	605	584
		Pos 2	554	577	552
	Group 2 50th Male	Pos 1	735	722	762
		Pos 2	719	724	738
	Group 3 95th Male	Pos 1	772	766	787
		Pos 2	762	744	768

Figure 32. Ergonomic distance in upright positions of the seats.

With the 680 mm as marked as the current minimum distance ECE R36, the 50th percentile were in comfortable position without contact with the front seat (except one case: the lowest and "stretched" seat position for the passenger, but only 1 mm exceeded). The maximum distance required to ensure the comfort is found for the 95th percentile male and with the lower seat, the step distance found were 787 mm.

Although this was not the aim of this project, it should be noted that for the 5th percentile female, an excessive height of the seat could be quite harmful, found difficulty in supporting the foot on the floor.

In the case where the seats were reclined (Figure 33), the greater distanced were imposed by the larger percentile (95th male) seated in the lower height seat. Now, the distance was produced with the passenger in a vertical position (the contact occurs at the knee rather than in the lower leg). With the minimum distance defined in the ECE R36, the 50th percentile male were not covered if the front seats were reclined or its seat was reclined, except for the highest seat.

			Reclined of the front seatback			Reclined of both seatbacks
			Seat test	Maximum	Minimum	
Distance L	Group 1 5th Female	Pos 1	592	601	584	603
		Pos 2	570	593	569	
	Group 2 50th Male	Pos 1	738	725	768	750
		Pos 2	743	725	768	
	Group 3 95th Male	Pos 1	785	768	807	797
		Pos 2	797	760	820	

Figure 33 Ergonomic distance when reclining back seats were done.

SAFETY STUDY.

In the safety study, the influence of the distance between seats for each type of evaluated restraint system (2 and 3 points safety belt) was analyzed separately. This fact is due to because it is possible that increasing the distance between seats is beneficial in a particular restraint system and detrimental in another restraint system and vice versa.

To clarify the study, first a summary table was shown with the results of the injury criteria from each dummy (tested in the short distance – row step distance of 737 mm). Subsequently, another figure was shown which analyzes the trend of the results using the following coding:

- + : Beneficial trend.
- = : No significant changes.
- − : Not beneficial trend.

3 points safety belt.

In the case of three points belted dummies (with two to four occupants), the results show that increasing the separation between seats produces a slight reduction in all injury criteria, except for the chest. While in either of the two configurations distance, all the calculations are sufficient below the limits set by regulation:

- The parameters of the injury of the head, neck, femur and knee decreases slightly. However the parameters of the chest injury (acceleration and deformation), slightly increased its value in the case of a greater distance between seats.
- This behaviour was expected, since with increasing distance, both the head and knees of the occupants virtually no impact with the seat back before them, and therefore, there was a reduction of the criteria measured in head and femur. On the other hand, being the passengers retained only by the belt, the efforts to which they subjected the chest are larger,

as shown in the highest loads recorded in the safety belts load cells and the maximum deformation of the chest.

In the case of seats with three-point belts and unbelted passengers, the results shown that increasing the distance was counterproductive because it results in several of the injury criteria are higher.

This increase is due to the fact that by increasing the distance between seats, the relative speed with which the occupants impacted with the back of the seat were being increased, as it was increased the free flight.

In the configuration of unbelted dummies and greater distance between seats, the knee slider criterion was slightly higher than the ECE R94 limit. Also the 3ms head deceleration is close to the limit of injury.

		Criterion	3 Rows (Bealted)		2 Rows (Unbealted		2 Rows (Bealted)	
			LD	RD	LD	RD	LD	RD
3 Points seat belt	R 80	Head HIC_{36ms}	183.63	192.48	219.98	216.46	202.94	204.92
		Head AcRes 3ms	33.37	32.93	66.76	67.37	59.61	61.49
		Right Femur Fz	1220.48	741.93	2736.66	2604.8	896.56	846.71
		Left Femur Fz	595.97	1215.26	2650.09	2610.3	1196.55	1240.32
	R 94	Neck My	-	-12.24	-	-29.13	-	-18.13
		Thorax AcRes	17.92	17.55	18.07	18.59	17.96	17.62
		Thorax V * C	0.005	0.0103	0.004	0.003	0.0073	0.0072
		Thorax Def	-5.85	-10.99	-2.48	-2.25	-8.03	-9.42
		Right Knee slider	8.88	3.53	11.72	13.62	8.16	9.35
		Left Knee slider	4.28	7.9	14.05	10.81	9.25	5.81

Figure 34. Injury criteria summary.

		Criterion	3 Rows (Bealted)	2 Rows (Unbealted	2 Rows (Bealted)
3 Points seat belt	R 80	Head HIC_{36ms}	+	-	+
		Thorax AcRes	=	-	-
		Femur Fz	+	-	+
	R 94	Head AcRes 3ms	+	-	+
		Neck Fx	+	+	-
		Neck Fz	+	-	=
		Neck My	=	-	+
		Thorax V * C	-	+	=
		Thorax Def	-	+	=
		Knee slider	+	-	+
	Total		6+; 2=; 2-	3+; 0=; 7-	5+; 3=; 2-

Figure 35. Comparison of injury criteria (3P).

2 points safety belt.

In the case of two points seat belt and four occupants, increasing the separation was a slight improvement in some calculated criteria, but not enough to prevent more of the calculated criteria were beyond the limits. The 3ms head acceleration and the extension bending moment of the neck exceeded the thresholds of injury for the two distances tested (737mm and 787 mm).

The slight improvement in safety seen in the four occupants configuration, was not confirmed in tests conducted with only two occupants. In this case, the long distance configuration, a slightly higher vales for the criteria for head and neck were registered, unlike in tests with dummies.

The criterion that produces a clear improvement for either configuration, it was in the femur load, although in both cases the values were sufficiently below of the limits established by ECE R80.

In the case of unbelted passengers, the results did not reflect a clear influence of distance on the safety offered to the occupants. The results obtained in tests in both configurations, were not very different, and only the neck extension moment was increased its values when the distance between seats is greater. In all cases, the neck extension values recorded were above the limit set by the ECE R94.

		Criterion	3 Rows (Bealted)		2 Rows (Unbealted		2 Rows (Bealted)	
			LD	RD	LD	RD	LD	RD
2 Points seat belt	R 80	Head HIC_{36ms}	392.43	413.44	205.98	189.13	326.33	298.37
		Head AcRes 3ms	88.81	91.81	70.18	67.77	75.84	76.04
		Right Femur Fz	1151.77	1601.83	2883.7	2634.07	1465.1	1809.76
		Left Femur Fz	1649.9	1519.59	2777.46	2862.69	1953.76	1838.85
	R 94	Neck My	-	-98.88	-	-70.18	-	-94.07
		Thorax AcRes	15.82	16.67	15.95	14.92	18.12	18.24
		Thorax V * C	0.0013	0.0013	0.0032	0.003	0.0039	0.004
		Thorax Def	-0.15	-0.06	-2.56	-2.23	-3.09	-4
		Right Knee slider	8.5	9.63	19.91	14.35	11.11	11
		Left Knee slider	9.74	10.26	13.75	6.88	10.04	11.68

Figure 36. Injury criteria summary.

		Criterion	3 Rows (Bealted)	2 Rows (Unbealted	2 Rows (Bealted)
2 Points seat belt	R 80	Head HIC_{36ms}	=	-	-
		Thorax AcRes	=	=	+
		Femur Fz	+	-	+
	R 94	Head AcRes 3ms	+	+	-
		Neck Fx	-	-	-
		Neck Fz	+	=	-
		Neck My	+	-	-
		Thorax V * C	=	=	+
		Thorax Def	=	=	+
		Knee slider	+	=	+
	Total		5+; 4=; 1-	1+; 5=; 4-	5+; 0=; 5-

Figure 37. Comparison of injury criteria (2P).

General discussion.

An increasing of the distance between seats was not an improvement of the security levels offered for all restraint systems analyzed. It has also reflected that the injury criteria established by the ECE R80 might be poor predicting injuries offered by the occupants. The ECE R94 (elaborately later) includes more injury criteria associated with impact dummy (this fact is independent of whether they are tested at 30 or 50 kph). It has been observed that the two points seat belts offered low protection in the neck. This fact is corroborated by Elias et al (2001 and 2003), which investigated the safety on school buses with similar conclusions. In addition, this study has verified that the levels of protection offered by unbelted occupants were limited. Through accidentological studies in Sweden, Albertsson et al (2003) concluded that a 2-point belt may have reduced injuries for two-third of all injured with MAIS 2–4 and a further injury reduction by 28% could be achieved by shifting 2-point belts into 3-point belts.

CONCLUSION.

To increase the comfort of coaches passengers authors recommended to establish a new seat spacing 50 mm higher that actual one, i. e 730 mm.

The effect of this new seat spacing in the passengers safety for the seats fitting 3 point belts is:

- If the safety belts are used the passenger protection is improved.
- If the safety belt is not used, the passenger protection will be lower, but nevertheless reaching the injury limits.

The effect of this new seat spacing in the passengers safety for the seats fitting 2 point belts remains unchanged.

To state of the results obtained in this study, it can be concluded that the requirements established by the regulation 80 to evaluate the passenger safety are not sufficient. It has been verified how in all the tests carried out with two point belts seats, they accomplish with all the requirements established by the Regulation ECE R80, but nevertheless, in some of the tests carried out in seats with two point belts, the injury criteria limits required by the ECE R94 have been overexceeded.

It seems logical to think that, if the R94 criteria are good to evaluate the security offered in frontal impact in a vehicle of the category M1, also they should be it for the case of the occupants from one of the category M3. Especially, when the injury criteria are associated to a specify dummy model and in a specific impact direction and not to the type of vehicle in which the tests are carried out.

For all it, it would be recommendable to revise the Regulation ECE R80 in order to incorporate the injury criteria defined in ECE R94. Doing this the passenger safety of coaches could be guaranteed in frontal impact accidents.

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REFERENCES.

[1] 1999 “Bus Crashworthiness Issues”. Highway Special Investigation Report. National Transportation Safety Board. Washington, DC 20594.

[2] Elias J. C. McCray L. Sullivan L. 2001 “Large school bus safety restraint evaluation”. 17th Enhanced Safety of Vehicles (ESV).

[3] Elias J. C. McCray L. Sullivan L. 2003 “Large school bus safety restraint evaluation – Phase II”. 18th Enhanced Safety of Vehicles (ESV).

[4] Walton A.C., Hashemi S.M.R, Anderson J.C. 2006 “Preventing Passenger Ejection from buses, coaches and minibuses” TTS Project Reference No: S0320/VE.

[5] Mitsuishi H. Sukegawa Y.Okano S. Nagase H. 2003 “Frontal Collision Safety of Bus Passengers in Japan” 18th Enhanced Safety of Vehicles (ESV).

[6] 2003 “Enhanced Coach and Bus Occupant Safety – ECBOS. Results and conclusions”

[7] Martínez L., Aparicio F., García A., Páez J., Ferichola G., 2003. “Improving occupant safety in coach rollover”. International Journal of Crashworthiness N8 Vol 2, pags 121–132.

[8] Regulation ECE 36R03. “Uniform provisions concerning the approval of large passenger vehicles with regard to their general construction”

[9] Regulation ECE 80R00 “Seats of large passenger vehicles”.

[10] Regulation ECE 94R01 “Protection of occupants against frontal collision”.

[11] Regulation ECE 107R02 “M2 and M3 vehicles”.

[12] SAE J211 1995 “Instrumentation for Impact Tests” SAE Recommended Practice.

[13] Schneider L.W., Robbins D.H., Pflüg M.A., Snyder R.G., 1983 “Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family, Volume I”. DTNH22-80-C-07502

[14] Kraus W. 2003 “The driver workstation in commercial vehicles”. Vol 1768. pp. 271-287 [Note(s):[350 p.]] [Document: 17 p.] (4 ref.) ISBN 3-18-091768-7.

[15] Garcia J, Quintana-Domeque C. 2007. “The evolution of adult height in Europe: a brief note”. Economics & Human Biology. Volume 5, Issue 2, July 2007, Pages 340-349.

[16] Albertsson, P., Bj¨ornstig, U., Falkmer, T., 2003. “The Haddon Matrix, a tool for investigating severe bus and coach crashes”. International Journal Disaster Medicine 2, 109–122.

IMPROVING MOTORCYCLISTS' SAFETY IN SPAIN BY ENHANCED CRASH TEST PROCEDURES AND IMPLEMENTATION GUIDELINES.

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ABSTRACT

Motorcyclist fatalities are a major road safety problem on Spanish roads. In 2006, 642 motorcyclists or cyclists fatalities occurred, which mean 21% of all road fatalities. More than half of them were run-offs. To address this safety issue, roadsides are equipped with so-called "Motorcyclist Protection Devices" (MPD). In 2005, the Spanish Standard UNE 135900 for the assessment of MPD was published, and Spanish National and Regional Road Administrations have been active in this field since then.

This paper describes research work aimed at improving motorcyclists' safety from a global approach, by two main activities:

- Upgrading the crash test procedure set by Standard UNE 135900, by implementing a new thorax injury criterion.
- Developing a methodology to recommend and warrant the installation of MPD on specific road stretches.

The implementation of a thorax injury criterion took into account the kinematics and injury causation process in the event of an impact of a motorcyclist sliding against a barrier. From the analysis of the response of bones, inner organs and vascular system it was concluded that loads measured on the vertebral column with a Hybrid III dummy are suitable to assess relevant thorax injuries. An injury criterion based on maximum vertical force measured on thorax was defined and implemented into the upgraded 135900 Standard.

The recommendations for the installation of MPD were based on analysing road sections and identifying bends with a higher risk of motorcyclist run-off collision, in order to install such devices with optimised cost effectiveness. The applied methodology comprised road inspections and epidemiological analyses in order to detect relevant risk factors.

As a result, a framework is provided that sets technical bases for the development and implementation of better motorcyclist protection devices, by assessing their performance through an enhanced standard, and by establishing scientifically–based criteria for their deployment.

INTRODUCTION

Run-off road accidents are those accidents involving vehicles that leave the roadway, encroach onto the shoulder and beyond, and impact any hazardous object located on the roadside, such as poles, trees, walls, or embankments. When a vehicle departs from the roadway, the severity of the accident can be reduced by removing obstacles or by installing appropriate protective devices. Road restraint systems, including safety barriers, are devices installed on roadsides to contain and redirect errant vehicles.

Motorcyclists or Powered Two-Wheelers (PTW) are vulnerable road users. In the event of a run-off accident, they have a high risk of suffering critical interaction with hazardous obstacles placed on the roadsides. To address this safety issue, roadsides are equipped with so-called "Motorcyclist Protection Devices" (MPD).

The safety performance of MPDs can be assessed by performing crash tests using anthropomorphic test devices (i.e. crash test dummies). Several crash test procedures have been developed in different countries [1] although the first Standard in this field was the Spanish Standard UNE 135900-2005 [2], published in 2005. This Standard became a reference for the development of new protection systems to be installed on roads. Since it was published in its first version in 2005, additional research has been performed to upgrade the Standard, which is presented in this paper.

Once that safe motorcyclist protection devices are available, road administrations are in charge of setting the policy for their installation on roads. However, given that resources are limited, it is not feasible to install MPDs on all bend sections of road networks. The choice of the locations where MPDs are to be installed should follow objective criteria that allow optimized safety benefits. The regional road administration of Castilla y León (CyL), in Spain, ordered an innovative research work with the objective to identify bends on roads where there is a higher risk of PTW run-off collision in order to install a MPD. The methodology followed in the research work is presented in this paper.

MAGNITUDE OF THE PROBLEM

The number of road accidents and fatalities has decreased during the last decade in areas such as North America and Europe. In the case of PTW users, while in United States nearly 10% of fatalities were PTW riders or passengers in 2004 [3], in Europe it increased to over 20% [4]. In the same year, 5,484 motorcycle and moped users (riders and pillion passengers) were killed in traffic accidents in 14 European Union countries, which is only 0.3% lower than the previous year. In the United States, this figure was 4,008 casualties, with an increase of 8% compared to 2003. In Spain, motorcycle and moped fatalities constituted the 18% and for the Spanish region of Castilla y León, motorcyclist and moped user stood at 11% of the fatalities.

Although PTW accident typology is wide, it has been found that impacts against fixed objects are more likely to provoke serious casualties in PTW run-off crashes. In the United States, collision with a fixed object was a significant factor in over half of the fatalities during single vehicle motorcycle crashes [5].

In Spain, from 2001 to 2006 PTW fatalities have decreased only by a 5.2%, while the overall reduction in the same period considering all types of vehicles has been 26.0%.

UPGRADING THE CRASH TEST PROCEDURE

Test procedure UNE-135900-2005.

The Spanish Standard UNE 135900-2005 sets the procedures to evaluate the performance of MPDs. They are based on launching a test dummy against a MPD installed on a safety barrier, which is assumed to feature vertical posts. The procedure covers MPD to be fitted on each post, as well as continuous ones. Depending on the kind of system to be tested, a different trajectory is chosen, from the following:

- Trajectory 1 – Centered post impact: applicable to individual post coverings and continuous MPDs with an approaching angle equal to 30º.
- Trajectory 2 – Eccentric post impact: applicable only to punctual MPDs. It follows a horizontal line that goes at a distance 'W' off the center of masses of the post, with an approaching angle equal to 30º.
- Trajectory 3 – Centered rail impact: applicable only to continuous MPDs.

The launching position is defined with the dummy spine axe coinciding with the approximation trajectory, and the dummy sliding along the ground, separated from the motorcycle, until it hits the protection system to be tested, with a specific entrance angle and speed. The dummy is a Hybrid III 50th Percentile Male, equipped with a pedestrian kit that allows a standing position, and is to be fitted with a full-front helmet, and a leather motorcyclist suit.

The assessment of the MPD performance is based on the evaluation of impact severity and additional acceptance criteria. For the evaluation of impact severity, the following measures are to be taken: HIC 36 for the head and Fx, Fy, Fz, Mx and My for the neck. The acceptance criteria regarding the behaviour of the safety device specify that no element of the crash safety barrier weighing 2 Kg or more should be separated from the device unless it is necessary for correct performance, and that the working width and dynamic deflection of the device on dummy impact should not be in any case equal or higher than those specified by the Standard UNE EN 1317-2 for vehicle impact. The acceptance criteria regarding the behaviour of the dummy specify that the dummy used for the test should not have intrusions, dummy breakage except the collar bone, be beheaded or suffer any dismemberment. Additionally, the dummy clothing should not be torn and, the dummy should not be caught on any part of the safety device.

The new thorax injury criterion

A potential improvement of the test procedure defined by UNE-135900-2005 that was proposed as an enhancement was the implementation of a thorax injury criterion.

For the definition of a thorax criterion, PMHS data were not available. It was decided to define a thorax injury criterion by using a crash test dummy, even taking into account that no dummy specifically developed for this kind of impact was available. The study was carried out applied to the Hybrid III dummy, taking into account that in an impact against a barrier, the injury causation process is as follows. Firstly the head and then the shoulder hit the lower plate of the barrier. The thorax loading initiates through the shoulder, fracturing the clavicle and deforming the upper ribs while the motorcyclist is guided along the barrier. Following this, the loading is transformed into an almost purely lateral one. Inner organs and the vascular system are bound to be affected by inertial effects. The main loads on the vertebral column are traction-compression and lateral-flexion.

Given that the Hybrid III thorax does not feature ribs, or measurement capabilities on organs and bones except for the vertebral column, it was decided that the proposed thorax injury criteria should be able to cover all relevant thorax injuries through the measurement capabilities available with the dummy instrumentation. This would be possible due to the inertial effects present as injury mechanisms for inner organs.

Thorax injuries had been analysed by military researchers [6], who studied the acceleration limits on PMHS and modified Hybrid III. They found correlations between the internal force limits of the column and the inertial effect on the organs. Rib fractures were not considered as a possible criterion, as multidirectional frangible ribs would have been needed, and in addition, once rib fractures occur, no additional information could be obtained beyond that point. Besides, the injuries with four or more rib fractures on one side or two, or three fractures with hemothorax or pneumothorax, are considered AIS3 (see Table 1).

Table 1.
Relationships between injuries and AIS severities

AIS Level	Rib Cage Injury	Thoracic Soft Tissue Injury
1	1 rib fracture	Contusions of the bronchus
2	2-3 rib fractures; sternum fracture	Partial thickness bronchus tear
3	4 or more rib fractures on one side; 2-3 rib fractures with hemothorax or pneumothorax	Lung contusion; minor heart contusion
4	Flail chest; 4 or more rib fractures on each of two sides; 4 or more rib fractures with hemothorax or pneumothorax.	Bilateral lung laceration; minor aortic laceration; major heart contusion
5	Bilateral flail chest	Major aortic laceration; lung laceration with tension pneumothorax
6		Aortic laceration with hemorrhage not confined to mediastinum

On the other hand, the force magnitude of an impact to the thorax is also transmitted directly to the column by the bones. It is for this reason that the most suitable place to calculate the severity of the impact is the vertebral column, particularly, when the dummy has available measurement points in that place.

An acceleration criterion can be used as it is done in military researchers but in case of motorcyclist test, the available point of interest to measure it is on t4 vertebra. The main problem to use an acceleration criterion was that the results are very sensitive to the spinal position, hyperextended, erect and flexed for example, that changes the fracture results 80% respect the others. On the other hand, acceleration criterion was quite sensible to a time dependency and the shape of the impact pulse. Thus, the investigations were focused on t9 vertebra, where Hybrid III dummy has an available force measurement point.

Research by Ruff [7] obtained values for average compression force causing vertebra fracture as a result of accelerations. In case of an ejection seat, these values correspond to a 21g for positive acceleration from pelvis and around 12g for negative acceleration applied on the shoulders. The force values depend on the age, and on the vertebra involved, as the percentage of body weight borne varies along the height of the vertebral column. The values obtained for the average force on t9 were 6.7

KN considering all ages, and 5.9 KN for people who are 23 years old. The latter value was deemed more suitable as young riders are often involved in accidents.

The measurement of compression force in thorax was introduced in the new updated Spanish Standard UNE-135900-2008 [8]. The enhanced procedure includes measuring and reporting vertical force Fz.

However, a limit value has not been set for this parameter. This is because current state of art has not yielded conclusive relationships between measured forces and injury severity, due to the fact that the load transfer by the different parts of the dummy during its interaction with the MPD may not be sufficiently biofidelic. Further research is needed, focused on the response of the dummy shoulder under oblique impact.

Discussion

Other studies that have been performed in parallel with the one presented in this paper suggest measuring Fy and Mx in the dummy thorax as suitable criteria to assess severity [1], [9]. Although their influence was not implemented in the current version of the Spanish Standard it is planned that ongoing and future revisions of the Standard will address this issue.

RECOMMENDATIONS FOR THE INSTALLATION OF MPD: METHODOLOGY

A methodology was developed for the regional Road Administration of Castilla y León, in Spain, in order to recommend and warrant the installation of MPD on specific road stretches. For that purpose, it was necessary to investigate which road infrastructure features have significant influence on PTW run-off accidents in order to detect those sections with higher probability of PTW run-off accidents. Among the features taken into account were curvature radius, bend length, road marking and signalling, road layout perception, and roadside configuration.

It was decided that the methodology would take into account the risk of a run-off regardless of the resulting severity, for two main reasons.

- Firstly, the severity of these accidents does not depend only on road infrastructure characteristics. Other aspects, such as rider speed, rider protection equipment and all the physical phenomena that occur during the complex event of the crash may condition the accident outcome.
- Moreover, studying all injury accidents makes a higher number of cases be available to be introduced in the statistical models.

In order to obtain reliable results about the road infrastructure risk factors, the following facts were taken into account:

- The accident study sample has to be precisely described, so that all cases where this problem cannot be isolated should be discarded.
- It is necessary to obtain highly detailed information about the accident and the road infrastructure features at the moment of the crash. Police record accident data are not enough to address this problem.
- Estimation of risk factors is based on information about those situations in which the accident does not take place (i.e. exposure to each of the possible risk factors). For instance, if the factor under analysis is “curvature radius lower than 100 metre (327.8 ft)” then it would be necessary to consider those motorcyclists who had suffered accidents at bends with radius below 100 metre, those who had suffered accidents at bends with radius above 100 meters, and as a counterpart, riders that had taken bends of both groups but had not been involved in an accident. Provided that these data are obtained, epidemiology is able to provide analysis methods for accident and non accident data.
- Possible sources of bias are controlled during the analysis as far as possible. For instance, differences between motorcyclists’ and drivers’ experience and capabilities were introduced in the analysis as co-variables in order to be controlled.

Based on such principles, the methodology applied to develop recommendations for the installation of MPD comprised the following main activities:

Descriptive Analysis

The first task set in the methodology was to describe the magnitude of motorcyclist run-off accidents within this regional road network. The Injury Accident Database of the Spanish region of Castilla y León was analyzed for this purpose. This database compiles all injury accidents. The variables in this database provide information relative to the three main components of safety, namely the road infrastructure (accident location characteristics), the vehicle (type and state of the motorcycle), and the rider (driving stereotype). This analysis provides macroscopic answers to the most relevant questions, i.e. where do PTW run-off crashes take place, how do they occur, and what kinds of riders are involved in them.

Once the problem is described at macroscopic level, a sample of representative road sections can be selected so as to obtain further information of all the possible factors of influence.

Integrated analysis of a selection of representative road sections

The objective of this phase of the project was to develop exhaustive data processing related to all the variables of the road infrastructure for PTW rider run-off crashes in the Spanish regional road network of Castilla y León.

Seven road sections were selected jointly with engineers from the Castilla y León regional road administration. All sections chosen complied with the following criteria: during three years prior to the study, each of the sections had had at least three PTW run-off injury accidents over a length of 1 km, and no main junctions were present within the section.

For all these sections the following set of analyses was performed:

- Specific road safety inspections were carried out by safety experts. The aim of these inspections was to assess the perception that riders may have of the road layout based on the fulfillment of a specific checklist.
- The road infrastructure inventory (software with all the road equipment and road layout geometry) of those road sections, owned by CyL regional administration, was crossed with the National Injury Accident Database and with accident files of the regional administration of PTW rider run-off accidents in those stretches of road.
- Then, all the road sections were recorded with video cameras. This enabled completion of the information of road safety inspections after the visits to the sections.
- Finally, 16 PTW rider's run-off accidents were investigated in-depth with to the methodology described in the following section (Figure 5).

This phase provided a complete matrix of data related to the rider, the vehicle and the road infrastructure features. It was used in the following phase for the application of epidemiologic methods in order to obtain the most significant road infrastructure risk factors for this type of accidents.

Risk Analysis

As stated previously, road administrations do not have unlimited resources implementing MPDs at every single problem area of road networks so it is necessary to know where a PTW run-off accident is more likely to occur and which road infrastructure parameters are the relevant risk factors associated with them.

Following an epidemiological approach, a risk factor can only be identified when data are available for four different parameters:

- How many PTW riders are exposed to the factor not having a run-off accident (a).
- How many PTW riders are exposed to the factor having a run-off accident (b).
- How many PTW riders are not exposed to the factor not having a run-off accident (c).
- How many PTW riders are not exposed to the factor having a run-off accident (d).

If these figures are available, the relative risk (RR) of a rider being involved in a run-off accident (if the factor is present compared to the situations when the factor is not present and assuming that other factors remain constant) can be estimated:

$$OR = \frac{a \times d}{b \times c} \qquad (1)$$

The above equation represents an odds ratio (OR). It can be considered as a relative risk always when the incidence of the accidents remains below 1% of the whole population [10]. In this situation, it can easily be assumed that much less than 1% of PTW displacements end with a run-off accident. Nevertheless, this approach only allows the study of one single factor at a time when all relevant factors could have influence simultaneously. In order to analyze the matrix of data developed in the previous stage, logistic regression models can be applied. They provide the estimation of the relative risks for all the relevant factors, taking into consideration the influence of the others.

With the available data, an observational epidemiological analysis was developed, as it is not possible to decide who is exposed to the different risk factors. A crossover case – control analysis was developed. The cases were motorcyclists involved in a run-off accident and the controls were motorcyclists not involved in a run-off accident. In order to properly identify cases and controls, the road sections analyzed in the previous step were selected so that no junctions were present in the section. Therefore, knowing the travelling direction of the motorcyclists that had an accident, the same motorcyclist was considered as a case in the bend where he had the accident and as a control in the previous bends where he did not have the accident. This can only be considered if the rider is known to have come from one of the ends of the road section. Therefore, the road section cannot include junctions to other roads.

This methodology enabled classification of the road network into four main groups (based on two initial parameters which were considered as risk factors) and then, for each of them, identification of the relevant road infrastructure risk factors for this type of accidents which were the basis for the development of the recommendations for the effective location of MPDs.

STUDY AND CHARACTERIZATION OF PTW RUN-OFF ACCIDENTS

The described methodology was applied specifically to the problem of motorcyclist run-off accidents in the road network of Castilla y León. The work was carried out as follows.

Descriptive Analysis

The first task in the study consisted of a descriptive analysis of the injury accident database that the government of the Castilla y León region has developed. The analysis was performed on all types of PTW injury accidents occurred in the regional road network over the last three years available (2002 to 2004). This analysis had the aim of finding out the main casuistry of these accidents (run-offs, side, front and sideswipe), characterizing them from a three angle research view (environment-human factor-vehicle). Special emphasis was placed on the information related to infrastructure (type of road, number of lanes, carriageway and lane width, road marking, hard shoulder, paved hard shoulder, road safety elements, road surface condition,…) as the project is focused on safety measures to be taken in the infrastructure management process.

The analyses included a variable that specified the type of PTW vehicle, due to the fact that a moped accident may have different mechanisms to one on a motorcycle. No significant differences were found in this study. 221 injury PTW run-off crashes were sorted out for the CyL road network from 2002 to 2004.

Figure 1 shows the distribution of motorcyclist accidents obtained from a sample of 242 accidents compiled from 15 regional Spanish road administrations

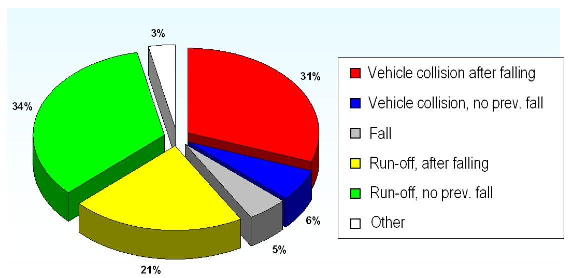

Figure 1. Accident types from a sample of PTW accidents in Spain.

Once PTW run-off accidents were identified as a relevant safety problem within the CyL road network and with the macroscopic overview from the descriptive analysis provided (type of roads, road layout, environmental conditions, day of the week, …), a sample of road sections was taken in order to obtain more detailed information about the rider, vehicle and all the road infrastructure characteristics in this type of accidents. The information included in police accident records is not detailed enough to analyze the real influence of the road infrastructure on this type of crashes. Therefore, it was necessary to obtain more data related to the accident itself and to the road infrastructure as a possible causal factor of PTW run-off accidents (e.g. it is not possible to know from police records: bend length, curvature radius or at which distance prior to the bend all the signals were visible).

The sample road sections were selected according to the following criteria:

- At least three PTW run-off accidents occurred within a road length under 1,000 m, during the period 2002 – 2004.
- No junctions with other roads (except local accesses to private properties) were present within the road sections.

All the road sections that complied with the above criteria were selected to apply the subsequent research activities.

In-depth accident analysis

One of the most important tasks of this project was the monitoring of all the PTW accidents over a period of one year in the regional road section with the highest number of motorcycle crashes.

This task had the aim of finding out, through the complete analysis of each accident, detailed information about these impacts: kinematics and dynamics of the accident (motorcycle and motorcyclist impact points, trajectories, impact angles, travelling and impact speeds for the motorcycle or the motorcyclist,…), complete scene characterization from the infrastructure point of view (layout, radius and length of curvature, element of sign-posting, alignment, slope, hump, surface status, pavement hard shoulders, embankments, benches,…), human factor information related to driver status before the impact, manner of driving and injury information in order to establish injury mechanisms. During that monitoring year, 16 injury accidents occurred on the road section selected (less than 20 kilometres length located in a mountainous area) involving 19 injuries and 2 fatalities.

The accident investigations developed at this stage are called 'in depth' investigations. They include all the inherent aspects to the accident which are analyzed in detail. The CIDAUT accident analysis and human factor team performed them. They can be classified into two types:

- Prospective, when the team, after receiving the accident notification from the police, attend the accident scene immediately;
- Retrospective, when it is not possible for the investigation team to be present at the accident scene immediately after its occurrence.

The main use of these investigations for this study were as follows: through the analysis of the accident scene, the checklist used in the road inspections was completed in order to consider road layout perception by the rider as this was essential in the 16 accident investigation. Moreover, some factors were identified as potential risk factors and therefore were included in the statistical analysis due to the outcome of these investigations (e.g. longitudinal slope, sighting distance of sign posts at the curve approach,).

Accident notification. The accident notifications (with or without injuries) were carried out by the police teams by forwarding information about the accident immediately after its occurrence. A specific direct collaboration with police patrols was established (immediate notification and supply of relevant information for the investigations).

Accident reconstruction. One of the advantages of the ‘in-depth’ investigations is the possibility of ascertaining some specific information which would be impossible to have in the so-called ‘basic’ investigations (which are carried out by police teams in all injury accidents). Through the information gathered by analyzing the scene (marks, debris or impact points which are drawn later in a detailed sketch) and the vehicles involved (deformations and impact points), it is possible to estimate some variables (e.g. travelling speeds) using different accident reconstruction techniques and specific software (PC Crash © [11].

Vehicle trajectory before and after the impact is one of the relevant issues of accident reconstruction. This is defined by the marks and debris found at the scene of the accident, and coincides with the deformations found in the vehicle and in the existing infrastructure (road restraint systems). The drawing of a detailed sketch, in which all the dimension-localization marks and debris are located, is fundamental for a reliable reconstruction of what really happened.

Considerations. The main aim of reconstructions is to find out all the useful information in order to determine which the possible concurrent factors in the accidents were. In addition to reconstructions, a speed radar was placed on the selected road section to observe what the traffic composition (number of passenger cars, light trucks, heavy trucks and PTWs) and the travelling speeds of each vehicle were. In 90% of the 16 accidents studied, high speed was clearly present. Data related to PTWs, showed, for instance, that in a 50 km/h speed limit bend, 85% of the PTWs were travelling at over 100 Km/h with a maximum registered speed of Km/h.

Road Safety Inspections

Road safety inspections were carried out on the seven selected road sections so as to investigate the infrastructure and its relationship with the present type of crashes. A checklist was developed in order to obtain detailed information about each bend of the selected road sections. It has a first general section in order to identify and describe the bend (location, length, weather conditions during the inspection, minimum curvature radius and its location within the bend and possible comments). Then, a questionnaire had to be filled out by road safety experts after driving and walking in both directions of each bend. The points addressed were as follows:

- Presence of hazardous elements for a motorcyclist in the event of a run-off accident on the outside of the bend or at its end.
- Location of the above hazards.
- Maximum depth of the roadside gutter.
- Perception of the road layout before approaching the bend and along it.
- Possible visibility restrictions within the bend.
- Possible road surface irregularities.
- Friction caused by the road surface.

The results of these checklists were put into the data matrix in order to be analyzed with the other information collated at this stage. Experts from the CyL regional road administration, CIDAUT and the PTW user group contributed in this activity.

Video recording and road infrastructure inventory

All the selected road sections were video recorded and GPS positioned. This allowed completion of the road safety inspections before and after visits to the sites. Precise data about road infrastructure data was a key element of this research. It was necessary to know for each selected bend reliable data about the real parameters of road infrastructure devices: bend length, curvature radius (along the bend as it does not remain constant), presence and location of signals and road markings, longitudinal slope and superelevation along the bend, lane width, description of the shoulder, presence of roadside restraint systems, …

The CyL regional administration provided the road infrastructure inventory software of the selected road sections. It contains a database where all the information about road network sections is covered together with the location of all variables. Combining the information from the police and in–depth accident files with the road infrastructure detailed information and also with completed road inspections checklists was made possible.

The result at this stage was basically a matrix with a detailed set of data prepared to be statistically analyzed in order to investigate which road infrastructure factors have more influence in PTW run-off accidents.

Obtaining risk factor for motorcyclist run-off accident

At this step of the research, statistical methods were applied to obtain the most relevant road infrastructure risk factors for PTW run-off accidents. The combined database used for the analysis contained 984 registers, of which 41 were cases (accidents) and 943 were controls (no accidents). P-values and confidence intervals were used for statistical significance testing. The variables considered from the data matrix were the following ones: Bend minimum curvature radius, curve length, location within the bend of the minimum curvature radius, decrease of the minimum curvature radius along the bend not predictable by the rider, bend sign posting and road marking, bend layout predictability at 150 m, 50 m and inside the bend, visibility restrictions, longitudinal slope, brow of a hill, superelevation, consecutive bends, PTW traffic flow, irregularities on the road surface, surface friction, paved shoulder, roadside hazard elements.

Due to the extent and type of CyL roads it was necessary to structure the network bends curves in different groups, easy to identify for traffic engineers, according to a few variables. Bend length and minimum curvature radius within the bend were chosen as the main variables to classify the segments. Nevertheless, it was necessary to define the critical values of those variables in order to classify the roads.

First, the variable bend length was statistically analyzed within the matrix data. Logistic regressions were developed in order to investigate which value of the bend length was statistically significant (level of confidence of 95%) as having influence in the PTW run-off accidents when the other variables were constant. Bend length values ranging from 20 meters to 390 were tested. The result of the test was the OR for the bend length codified as binary for each tested value and its corresponding p–value. The reference value 120 metres provided the narrowest confidence interval, the 'p–value' being less than 0,05 and was chosen as the value to divide the road network into two initial groups.

The minimum curvature radius within the bend for each group was similarly analyzed, for each group of roads according to bend length, in order to obtain which reference value for this variable had more influence on this type of crashes. This value was of 90 meters. Therefore, the road network bends were divided in four different scenarios (Table 2).

Table 2.
Description of the scenarios for bend classification

Scenario nº	Curve length	Minimum curvature radius
1	> 120 m	> 90 m
2	> 120 m	< 90 m
3	< 120 m	> 90 m
4	< 120 m	< 90 m

At a second stage, for each later group which road infrastructure variables having an influence as risk factors in PTW run-off accidents were investigated.

Crossover case–control analysis was applied for each group and the statistically significant risk factors were identified (p–value < 0,05 and confidence intervals not including '1' at a confidence level of 95%). A p-value below 0,05 for an estimation of an odds ratio shows that the probability of accepting the value of the odds ratio (alternative hypothesis) is real. Those road infrastructure significant factors presenting an odds ratio above '1' turned out to be risk factors.

A relative risk (estimated in this research through the odds ratio) above '1' for a factor means that it increases the probability of having an accident, compared to the same situation in absence of the factor, by (OR -1) x 100%.

Apart from the statistical results of each logistic regression model, a road safety interpretation of the validity of those results was also investigated by safety experts in order to give coherence to the results. This was the basis for the development of the recommendations for the effective location of MPDs.

RESULTS

The statistical analysis performed over the combined database created for this project enabled the definition of the final criteria for locating MPDs in CyL road network to be made. This complete database contained all the information from the different tasks detailed in the previous sections:

- Macroscopic statistical analysis of the regional accident database.
- Macroscopic statistical analysis of the road section with the highest number of PTW accidents.
- Detailed information from the 16 'in-depth' accident investigations.
- Information from the road safety inspections of all the bends from the seven road sections.
- 'Road Infrastructure Inventory' software related to the previous seven road sections.

The objective of structuring the road network in the four scenarios presented in the previous section is to analyze the specific casuistry of each scenario. The election of these 'main segmentation variables' has been based, besides being statistically significant, on the need of being able to decide, in a reliable, simple and effective way, whether a certain bend belongs to a certain scenario or another. For each scenario, the different statistical influence was analyzed for all the variables of risk that a motorcyclist suffers in a run-off. Thus, recommendations for the MPD installation were developed for each one of the four scenarios mentioned in the previous section of this paper.

The final variables that were more relevant for the geometric segmentation of all the bends from the total network ('main segmentation variables') were bend length and bend minimum curvature radius. The justification of choosing those 'limit values' for these two main variables is based on the statistical methodology applied:

The joining of these two 'segmentation variables' gives us the four scenarios for simple regional road network classification. Recommendations for MPD location were developed for each one.
Once the four scenarios were defined, new tests were performed to determine which variables were relevant as risk factors in run-off accidents. The selection of the final variables was based on the ‘p-values’ from the different statistical tests done over these variables.

The final variables considered as criteria for each scenario to determine where MPDs must be installed in the road network in Castilla y León were the following (Table 3):

Table 3.
Variables to be taken into account for MPD installation in each scenario

Scenario	Variables to be considered
1	1. Road Signs and road marking for the definition of bend layout. 2. Position of decrease of minimum curvature radius along the bend not predictable by the rider. 3. Isolated bend
2	1. Road Signs and road marking for the definition of bend layout. 2. Position of decrease of minimum curvature radius along the bend not predictable by the rider. 3. Isolated bend.
3	1. Road Signs and road marking for the definition of bend layout. 2. Location within the bend of the minimum curvature radius. 3. Position of decrease of minimum curvature radius along the bend not predictable by the rider.
4	1. Location within the bend of the minimum curvature radius. 2. Isolated bend. 3. Paved shoulder.

The position of the MPDs should be on the outer side of the bend and along its whole length. In bends fulfilling the conditions of one of the scenarios where there is no roadside restraint system, this should be installed together with an MPD. Besides, it was observed that in consecutive bends where at least one fulfilled criteria, MPDs must also be placed in areas of adjacent bends.

CONCLUSIONS

The present research has provided a scientific basis for the development and implementation of better motorcyclist protection devices, in two stages. The first one is assessing their performance through an enhanced standard, which will foster the development of products with increasing safety performance for users. The second one is the development of recommendations for an effective location of MPDs within the Spanish regional network of Castilla y León.

Specific recommendations were provided for four different scenarios, grouped according to the curve length and minimum curvature radius. The research has combined data from different and complementary sources: police data, in-depth accident investigations, road infrastructure inventory, road safety inspections, accident cases and non accident control data. Future improvements could be developed by carrying out a monitoring period after the implementation of MPDs as a result of these recommendations. No previous study was found on the application of epidemiological techniques on road layout design for motorcyclists, which underlines the innovation of this research.
Epidemiology applied methods enabled assessment of the relative risk of the significant road infrastructure factors on PTW run-off accidents. The road sections where those risk factors are present are subject to MPD installation.
The application of these recommendations is to contribute to reducing serious injury to PTW riders within the Spanish regional road network of Castilla y León. In addition, once the MPDs have been put in place according to these recommendations, their effectiveness in reducing PTW rider injuries is being monitored so that the safety benefit achieved is ultimately evaluated

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REFERENCES

1 S. Peldschus , E. Schuller, J. Koenig, M. Gaertner, D. García, A. Mansilla, "Technical bases for the development of a test standard for impacts of powered two-wheelers on roadside barriers," Proceedings of the 20th Enhanced Safety of Vehicles Conference, 2007.

2 Spanish Standard UNE-135900-2005, "Standard on the evaluation of performance of the protection systems for motorcyclists on safety barriers and parapets"

3 United Nations Economic Commission for Europe. Statistic of Road Traffic Accidents in Europe and North America. New York and Geneva, 2007.

4 Association des Constructeurs Européens de Motocycle. ACEM´s view on PTW fatality statistics in Europe. Brussels, 2006.

5 National Highway Traffic Safety Administration. Fatal single vehicle accident. DOT HS 809 360, Washington, October 2001.

6 Advisory Circular from US Department of Transportation. Federal Aviation Administration. "Injury criteria for human exposure to impact". AC Nº21-22. Date 6/20/85

7 "Survivable impact forces on human body constrained by full body harness". HSL/2003/09.

8 Spanish Standard UNE-135900-2008, "Standard on the evaluation of performance of the protection systems for motorcyclists on safety barriers and parapets"

9 APROSYS SP4, "Advanced Protection Systems", Integrated European Project, VI Framework Programme. www.aprosys.com

10. J. de Irala, M.A. Martínez-González, M. Seguí-Gómez. Applied Epidemiology. Ariel Ciencias Médicas. Barcelona, 2004.

11 . Datetechnik Steffan. *PC-CRASH Simulation Program for Vehicle Accidents. Version 7.0.* Linz, Australia, November 2002.

STATUS OF NHTSA MOTORCOACH SAFETY PLAN

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ABSTRACT

The United States Department of Transportation, National Highway Traffic Safety Administration (NHTSA), has been actively researching ways to improve bus safety for several years. In 2007, NHTSA completed a broad review of motorcoach safety issues in the United States and developed an approach that would be pursued to most expediently address those issues. This paper discusses the priority areas that are being investigated for improvements, presents the approach that is being taken in each priority area, and summarizes the status and research results obtained thus far.

While there are a number of agency programs that encompass motorcoaches, the agency has decided to pursue these efforts as priorities: passenger ejection, roof strength, fire safety, and emergency evacuation.

For passenger ejection, incorporation of seat belts has been pursued as the most expedient way to mitigate ejection. A full scale frontal 30 mph barrier crash test was conducted to measure the occupant responses for both belted and unbelted conditions, and sled testing under a variety of configurations was completed to assess seat anchorage and seat belt load experienced under these conditions.

Regarding roof strength, tests on four motorcoaches were conducted to assess and compare European and U.S. requirements for roof strength in buses. Survival space and emergency exit operation were studied for both test conditions.

To address emergency evacuation on motorcoaches, studies and human evacuation simulations are being conducted. Various emergency exit scenarios including windows, rear stairs/door, existing wheelchair exit doors, airplane style portals, and roof exits are being evaluated. Minimum strength requirements for opening emergency exits based on the age of the occupant are also being examined.

As for fire safety, NHTSA is conducting research to examine how a motorcoach fire spreads from the wheel well to and through the passenger compartment. The flammability of interior and exterior materials will be investigated, as well as detection systems to warn the driver of an external fire along with automatic suppression systems to quell a fire before it spreads.

INTRODUCTION

Motorcoach transportation has been a very safe form of transportation in the United States. On average, about 14 fatalities have occurred annually to occupants of motorcoaches in crash and rollover events, with about 2 of the fatalities being drivers. Approximately one-third of the fatal crashes resulted in rollover. Ejection of passengers from motorcoaches accounts for approximately one-half of passenger fatalities. Among all motorcoach crashes, about two-thirds are single vehicle events and involve running off the road, hitting roadside objects, or rolling over.

In addition to the fatal crashes, there have been a number of fire incidents, including a tragic incident in Wilmer, Texas [NSTB, 2007] resulting in the death of twenty-three occupants when a fire erupted to engulf the motorcoach.

In 2007, following completion of several studies relevant to motorcoach safety, NHTSA conducted a comprehensive review of those studies and motorcoach safety issues in the United States, and then developed an approach that would be pursued to most expediently address those issues [NHTSA, 2007]. This paper discusses the priority areas that are being investigated for improvements, presents the approach that is being taken in each priority area, and summarizes the status and research results obtained thus far.

PASSENGER EJECTION

Passenger ejections can be reduced by using a number of different technologies, e.g., reducing openings by using stronger window retention methods, improvements to the integrity of window and other glazing areas, use of safety belts etc. Crash and sled tests to study the effects of using safety belts are described in the following sections.

For passenger ejection, a full scale frontal 30 mph barrier crash test was conducted to measure the occupant responses for both belted and unbelted conditions, and sled testing under a variety of configurations was completed to assess seat anchorage and seat belt load experienced under these conditions. These tests are described in the following.

Crash Test

The agency conducted a crash test in December 2007 at the NHTSA Vehicle Research and Test Center in E. Liberty, Ohio (Test # 6294 in NHTSA Vehicle Crash Test Database). Figure 1 shows the motorcoach used in the test. It was a 2000 MCI 102EL3 Renaissance with a Series 60 diesel engine and B500 Allison Automatic transmission. The coach was 45 ft long, 12 ft 6 inches tall, with 54 seats (34 inches apart longitudinally). The weight as tested (including dummies and equipment) was 42,720 lbs.

Figure 1. Motorcoach Used for Crash Test

The coach had unbelted seats from American Seating Co, seats with 2 and 3-point belts from Amaya/Fainsa and a seat with 3-point belts from Freedman Seating Co.

The crash test speed was 30 mph (48.3 kph) into a fixed rigid barrier at 0 degrees, full overlap condition. The test collected data from 355 dummy channels and 26 vehicle channels at 12,500 samples/sec. Figure A1 in Appendix A shows the crash pulse (deceleration) from three locations in the middle and rear of the coach, away from the crush zone.

The coach had the following dummies on-board:
•Hybrid III 50th male – 17 dummies
•Hybrid III 5th female – 3 dummies
•Hybrid III 95th male – 2 dummies

Each dummy had accelerometers in head and chest, load cells in upper neck and femur, and a chest displacement potentiometer. The dummies were seated at locations shown in Figure 2.

Crash Test Observations

Unbelted dummies had high head accelerations and neck injury values (Nij), as did the dummies with 2-point (lap) belts. The highest readings of the Head Injury Criteria (HIC15) and Nij in unbelted dummies were approximately twice the Injury Assessment Reference Value (IARV) (1.9 and 2.1 respectively). The corresponding ratios of the highest HIC15 and Nij for dummies with lap belts were 1.9 and 4.7 respectively.

The injury criteria and the IARV are described on the Advanced Air Bag Technology page on the NHTSA web site.
http://www-nrd.nhtsa.dot.gov/

The dummies restrained by 3-point belts had low injury assessment values for head and neck. The highest HIC15 and Nij in dummies with lap and shoulder belts were 0.6 and 0.8 respectively. All dummies had low chest accelerations, chest displacements and femur loads (worst case condition of about half of the IARV).

Unbelted dummies typically made head contact with the seatback in front within 150-180 ms. The unbelted dummies in the aisle seat ended up in the aisle, while those in the window seat ended up in the row in front or on the floor.

Structurally, all seats remained attached to the bus at all seat anchor locations. One baseline (unbelted) seat had a failure of the seat frame at

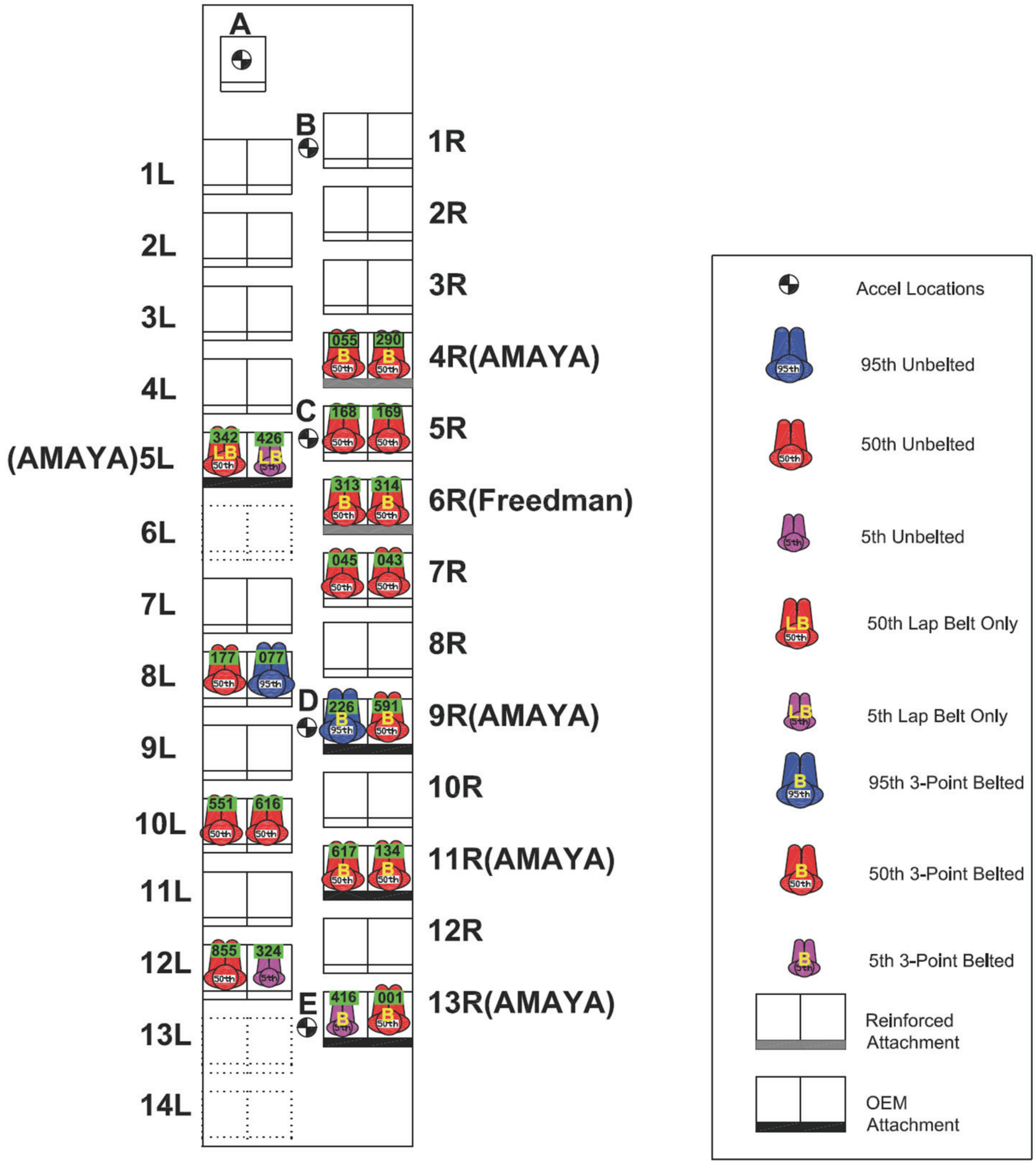

Figure 2. Motorcoach Crash Test Dummy Seat Diagram

the floor attachment. This unoccupied seat had unbelted 50th M and 95th M in the row behind it. Baseline seats and the Freedman seat had bent/broken seatbacks when impacted by unbelted dummies in the seat behind it. Figure 3 is an image from the crash test.

Figure 3. Belted Dummies (on left) Remained in Their Seats; Unbelted Dummmies (on right) Did Not.

Sled Tests

Fifteen crash simulations (sled tests) were run using a representation of the crash pulse from the crash test at VRTC (VRTC Pulse). Additionally, five sled tests were run using the European ECE Regulation 80 tests of seats and anchorages (EU Pulse). The crash test acceleration, VRTC Pulse and the EU Pulse, including the corridors used to define the EU pulse requirements, are shown in Figure A2 in Appendix A. The approximate velocity change for the VRTC pulse was 25 mph (40.2 kph) and for the EU pulse was 20 mph (32.2 kph). These tests are available in NHTSA Vehicle Crash Test Database as test # 6559 through 6578.

Three types of seats were used in the sled tests.

1. Baseline (American Seating)
    a. No belts

2. M3 belted seats (Amaya/ FAINSA)
    a. 3-point belts
    b. 2-point belts

3. M2 belted seats (Amaya/ FAINSA)
    a. 3-point belts

Baseline seats without seat belts were obtained from the 2000 MCI 102EL3 Renaissance Series tested bus and the seat supplier, American Seating Company (Amer Seat).

Three different seats with seatbelts, supplied by Amaya/FAINSA, were used in the sled tests. These seats were designed to meet ECE Regulation 14 and TRANS/WP.29/78/Rev.1/Amend2

M3: These seats are designed for mass transportation vehicles having a mass exceeding 5 tonnes (11,023 lbs). This uses a load equivalent to 6.6g. (referred to as “7G seats” in Figure 4).

M2: These seats are designed for mass transportation vehicles, having a mass not exceeding 5 tonnes (11,023 lbs). This uses a load equivalent to 10g. (referred to as “10G seats”). All such seats used had 3-point seat belts and are similar in appearance to the M3 seats.

The test matrix is shown in Figure 4. The test setup consists of three rows of seats with the middle row, subject seat, having load cells at all the seat anchor locations. Figure 5 shows a typical buck setup. The occupants at the 6 possible seating locations are as shown in Figure 4 along with crash pulse and the type of belted seat used. The test numbers used are as follows:

TEST N
Test # YYMMDD - Test sequence for that day

where N is the chronological sequence of tests in the order they were run (1 through 20).

0 DEGREE BUCK ANGLE

TEST Type / *Test Obsevation*	*ROW*	*SEAT*	*DUMMY LOCATIONS* *Restraint* Left	Right	TRC Test # *7G seats* VRTC pulse	*7G seats* EU pulse	*10G seats* VRTC pulse
1	Front	Amer Seat	--	--	TEST 4	TEST 16	TEST 15
Seat Forces	Middle	Amaya/FAINSA	95th 3pt	95th 3pt	Test # 080721-1	Test # 080820-1	Test # 080819-1
Maximum	Rear	Amer Seat	95th unbelt	95th unbelt			
2	Front	Amer Seat	--	--	TEST 5	TEST 17	TEST 13
Seat Forces	Middle	Amaya/FAINSA	50th 3pt	50th 3pt	Test # 080722-1	Test # 080821-1	Test # 080815-2
Medium	Rear	Amer Seat	50th unbelt	50th unbelt			
3	Front	Amer Seat	--	--	TEST 3	TEST 18	
Seat Forces	Middle	Amaya/FAINSA	50th 3pt	50th 3pt	Test # 080716-2	Test # 080821-2	
Average	Rear	Amer Seat	--	--			
4	Front	Amer Seat	--	--	TEST 2	TEST 19	
Seat Forces	Middle	Amaya/FAINSA	50th 3pt	5th 3pt	Test # 080716-1	Test # 080822-1	
Minimum	Rear	Amer Seat	--	--			
5	Front	Amer Seat	--	--	TEST 1	TEST 20	
Lap Belts	Middle	Amaya/FAINSA	50th 2pt	5th 2pt	Test # 080715-1	Test # 080822-2	
	Rear	Amer Seat	--	--			
6	Front	Amer Seat	--	--	TEST 7		
Compartmentalization	Middle	Amer Seat	95th unbelt	95th unbelt	Test # 080724-2		
Current	Rear	Amer Seat	5th unbelt	5th unbelt			
7	Front	Amaya/FAINSA	--	--	TEST 6		
Compartmentalization	Middle	Amer Seat	50th unbelt	5th unbelt	Test # 080724-1		
Seat Effects	Rear	Amer Seat	50th unbelt	5th unbelt			
7b	Front	Amaya 10G	--	--			TEST 14
Compartmentalization	Middle	Amaya 7G	50th unbelt	5th unbelt			Test # 080818-1
Seat Effects 10 G	Rear	Amer Seat	50th unbelt	5th unbelt			
10	Front	Amaya/FAINSA recl	--	--	TEST 12		
Reclined	Middle	Amaya/FAINSA recl	5th 3pt	50th 3pt	Test # 080815-1		
Belted	Rear	Amer Seat	50th unbelt	50th unbelt			
11	Front	Amaya/FAINSA	--	--	TEST 10		TEST 11
Max Rear Loading	Middle	Amaya/FAINSA	5th 3pt	50th 3pt	Test # 080813-1		Test # 080814-1
Belted	Rear	Amer Seat	95th unbelt	95th unbelt			

15 DEGREE BUCK ANGLE

TEST Type / *Test Obsevation*	*ROW*	*SEAT*	Left	Right	7G seats VRTC pulse	7G seats EU pulse	10G seats VRTC pulse
8	Front	Amaya/FAINSA	--	--	TEST 8		
Compartmentalization	Middle	Amer Seat	5th unbelt	50th unbelt	Test # 080729-1		
Current	Rear	Amer Seat	5th unbelt	50th unbelt			
9	Front	Amer Seat	--	--	TEST 9		
Compartmentalization	Middle	Amaya/FAINSA	5th 3pt	50th 3pt	Test # 080730-1		
Belted	Rear	Amer Seat	5th unbelt	50th unbelt			

[green shading] = The test condition was replicated in the crash test

	Front row	--	--	--	
↑	Middle Row	--	--	--	This row has seat anchor load cells
Direction of impact	Rear Row	--	--	--	

Test #: YYMMDD - Test sequence #

Test 11 used 10g seat in the middle row, 7g seat in the front row

Figure 4. Motorcoach Sled Test Matrix

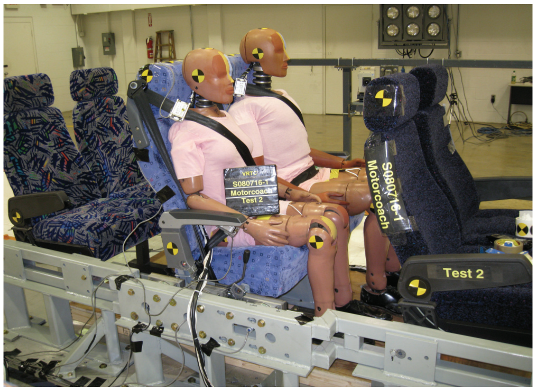

Figure 5. General Sled Buck Setup

Each seat was attached at 4 locations; 2 on the floor, and 2 on the side. These are marked in Figure 6 as locations A, B, C, D, respectively. For the sled test program, the center row seat was mounted at the 4 locations with rigid attachments with 3-axis load cells. Forces in 3 directions were measured at each of the seat anchor locations.

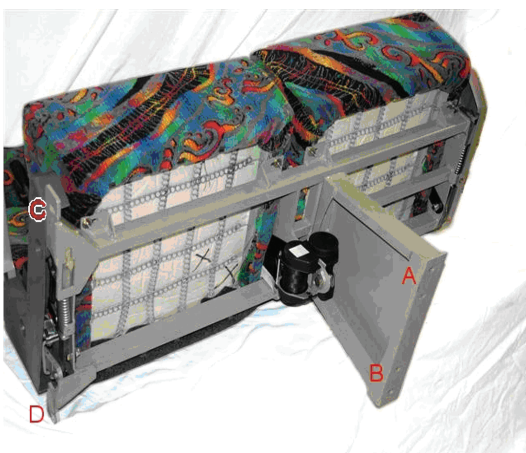

Figure 6. Motorcoach Seat Anchor Locations

Sled Test Observations

Higher dummy injury assessment values were mostly limited to HIC and Nij. The 3-point belted seats prevented critical injury values in almost all configurations with VRTC crash pulse. No 3-point belted dummy recorded a critical Nij across all test conditions

Unbelted dummies loading the target seat from the rear often increased the injury values of the 3-point belted dummy in the target seat, when compared to tests that had no rear dummy loading.

The EU pulse has a shorter duration and higher peak G than the VRTC pulse. EU pulse tests resulted in higher HIC when compared to VRTC crash test pulse. Three-point belted dummies with the EU pulse reached critical injury values in tests.

Dummy injuries values (HIC and Nij) reached critical thresholds with 2-point (lap only) belt tests. The 5th female dummy consistently recorded higher injury numbers when compared to the larger occupants in 2-point and unbelted conditions.

Low injury numbers were recorded for 15 degree angled testing. However, the unbelted dummies were not contained between the seats and often fell into the 'aisle.'

For similar tests with the Amaya M2 and M3 seats, the injury values were relatively similar.

ROOF CRUSH/ROLLOVER TESTING

Roof crush/rollover testing was performed on two different motorcoach models. The testing was done to evaluate two existing roof crush/rollover test procedures on four older motorcoaches: Federal Motor Vehicle Safety Standard (FMVSS) No. 220 and Economic Commission for Europe (ECE) R.66 complete vehicle test.

The agency tested two 12,200 mm (40 feet) 1992 Motor Coach Industries (MCI) model MC-12 and two 1991 Prevost model LeMirage motorcoaches. MCI and Prevost vehicles were selected to "bracket" the roof strength characteristics for similar sized motorcoaches in the fleet. The most evident structural difference was that the Prevost LeMirage had smaller side windows and more roof support pillars than the MCI MC-12. Table 1 presents information about each of the buses.

Previous Related Research

From 2003 to 2006, NHTSA and Transport Canada had a joint program focused on improving glazing and structural integrity of motorcoaches to prevent ejections, using standard coach windows and different variations of glazing and bonding techniques [NHTSA, 2006]. The research focused on finite element modeling of a Prevost model during a rollover. The simulation computed the force applied to the roof during the ECE R.66 rollover test, and during other scenarios such as sliding into fixed objects. The key findings of the research with respect to force on the roof indicated that a force of 1,149,529 N (258,424 lbs) (approximately 7.6 g's average acceleration) with an applied vector angle of 29 degrees relative to the bus longitudinal-transverse plane was achieved during the rollover. It was determined that the average force distribution along the top corner of the bus was approximately 86 N/mm (490 lbs/in) along the length of the bus.

Existing Test Protocols

Two existing roof crush/rollover protection test procedures and their associated performance requirements for buses were examined to determine the feasibility of their application to motorcoaches sold in the United States. One procedure is that specified in FMVSS No. 220, "School Bus Rollover Protection," and the other is that specified in ECE R.66, "Uniform Technical Prescriptions Concerning The Approval Of Large Passenger Vehicles With Regard To The Strength Of Their Superstructure."

FMVSS No. 220 specifies performance requirements for school bus rollover protection. It specifies that when a uniformly distributed load equal to 1.5 times the unloaded vehicle weight (UVW) is applied to the vehicle's roof through a force application plate, the downward vertical movement at any point on the application plate shall not exceed 130 mm and the emergency exits must be operable during and after the test. The force application plate is positioned along the longitudinal centerline of the roof and is 914 mm (36 inches) wide and 305 mm (12 inches) shorter in length than the vehicle roof.

ECE R.66 applies to single-deck, rigid or articulated vehicles, designed and constructed for the carriage of more than 22 passengers in addition to the driver and crew. ECE R.66 requires a complete vehicle test but allows alternative tests which are based on the full vehicle test. The complete vehicle test was conducted for this research program.

In the complete vehicle test, a bus with a blocked suspension is placed on an 800 mm (31.50 in) high tilting platform. The bus is tilted slowly to its side until it reaches its unstable equilibrium and tips onto a horizontal, dry and smooth hard surface.

The performance specifications of ECE R.66 require that the superstructure of the vehicle have sufficient strength to ensure that adequate residual space to survive a rollover is maintained during and after the rollover test. Templates for the ECE R.66 defined residual space are placed inside the vehicle in the front, center and rear of the bus. The requirements are such that no part of the vehicle which is outside the residual space at the start of the test (e.g. pillars, safety rings, luggage racks) shall intrude into the residual space during the test.

Test Results

The testing demonstrated that it is possible to apply the FMVSS No. 220 test or the full vehicle test in ECE R.66 to motorcoaches. The results of the testing are presented below.

For the FMVSS No. 220 tests, neither of the two motorcoaches tested were able to attain the 1.5 x UVW loading that is required according to the specifications in FMVSS No. 220 for school buses. The testing showed that the front sections

Table 1.
Manufacturer's Bus Specifications for Roof Crush Testing

Make	Model	Model Year	Unloaded Vehicle Weight	GVWR	Window Length (mm)	Window Height (mm)
MCI	MC-12	1992	12,474 kg (27,500 lbs)	17,146 kg (37,800 lbs)	1310	685
Prevost	LeMirage	1991	12,426 kg (27,395 lbs)	18,145 kg (40,000 lbs)	815	1040

of these two bus models were weaker than the back. This is most likely because the windshield and service door were located in the front of the bus and offered little resistance to the compressive load. Deformation at the front of both buses was such that the luggage racks entered the residual space as defined in ECE R.66. The front of the MCI bus yielded to the compressive load at 0.91 x UVW, while the front of the Prevost bus yielded at 1.17 x UVW. One of the possible reasons for the differences in the two buses is the number and size of the pillars. The MCI bus had seven pillars, 57 mm (2.24 in) wide, while the Prevost bus had 10 pillars, 205 mm (8.07 in) wide. While other properties such as material and cross-sectional shape play a role in compressive strength, the results tend to indicate a relationship to the number of pillars.

For the ECE R.66 tests, the interior sidewall of both motorcoaches entered the residual space at the front of the occupant compartment. Each bus was positioned on the tilting platform with the driver's side (left) adjacent to the platform's hinge. The platform was raised at a steady rate of less than 5 degrees/second until the vehicle reached its unstable equilibrium and commenced its roll, which occurred at approximately 48 degrees from the horizontal (MCI) and 51 degrees from the horizontal (Prevost). Both buses struck the ground near the left upper edge of the vehicle just above the windows. In both tests, the vehicle windshields lost retention, the emergency roof exits opened, and the front residual template made contact with the left side window. In the MCI bus, the left side luggage rack inboard hangers rearward of the front two hangers broke during the impact, leaving exposed sharp metal edges.

Accelerometers were installed on the impact-side interior corner of the roof within the same lateral planes as the residual space templates. The average accelerations along the top of the bus roof when the bus struck the ground surface were calculated. The average accelerations from the roof accelerometers when the buses impacted the ground ranged from 7.59 (MCI) to 8.2 (Prevost) g's. These average acceleration values agree very well with the Transport Canada simulation study that indicated an average roof acceleration of 7.6 g's on a 13,420 mm (44 ft) Prevost bus.

Energy Analysis Quantitative Assessment

In an effort to quantitatively assess the relative stringency between the FMVSS No. 220 and the ECE R.66 tests, a review of the energy absorbed by the buses in each of the two tests was examined. Table 2 presents the energy absorbed by the MCI and Prevost buses in the FMVSS No. 220 and ECE R.66 tests. The energy absorbed by the two buses in the ECE R.66 test is 2.5 to 3 times greater than that at the maximum applied energy in the FMVSS No. 220 test. Both buses experienced vertical displacement of the load application plate that exceeded the maximum allowable level of 130 mm (5 1/8 inches) in the FMVSS No. 220 tests. Additionally, both buses crushed into the ECE R.66 survivable space templates in both the FMVSS No. 220 and the ECE R.66 tests. Since both the buses did not meet the FMVSS No. 220 requirement for school buses sold in the U.S. and ECE R.66 requirements for motorcoaches sold in the EU, it is not possible to objectively assess the relative stringency of these two tests with the available information. Also, since the ECE R.66 test is a dynamic event while the FMVSS No. 220 test is a quasi-static event, and since the load applications in the two tests are significantly different, the absorbed energy cannot be directly compared.

Table 2
FMVSS No. 220 and ECE R.66
Energy Analysis

	Mass (kg)	Energy at 130 mm crush (J)	Energy at Maximum Achievable Load		ECE r.66 Potential Energy (m*g*Δh)	
			UVW	(J)	CG Δh (m)	Energy (J)
MCI	12,700	4,444	0.91	33,960	0.840	104,653
Prevost	13,381	7,140	1.17	37,599	0.723	94,906

Qualitative Analysis

While it was not possible to quantitatively assess the relative stringency between FMVSS No. 220 and ECE R.66, it is possible to perform a qualitative assessment. From a qualitative basis, it appears that the FMVSS No. 220 criteria for school buses may be more stringent than the rollover requirements in ECE R.66 for buses meeting that regulation. This is based on the observation that neither of these buses was able to support its UVW in the FMVSS No. 220 tests and failed catastrophically prior to reaching 1½ times UVW. Both of the buses crushed approximately 355 mm (14 in) to the top of the ECE R.66 defined residual space template before contact with the luggage rack. The MCI bus reached the 130 mm (5.118 in) maximum displacement criteria for school buses at approximately 70 percent of UVW, and the Prevost bus reached the displacement criteria and continued to displace at 100 percent of the UVW.

During the ECE R.66 rollover tests, imprints from the residual space templates where the front templates struck the side windows in both the MCI and Prevost coaches indicate that only the lateral corner of the templates struck the side window. This suggests that with some design improvements to counteract the lateral forces these buses could pass the ECE R.66 rollover test.

In severe rollover incidents where the bus rolls over more than a quarter turn, school buses meeting FMVSS No. 220 have shown remarkable ability to maintain their structural integrity. Based on the above observations, it appears that the FMVSS No. 220 test protocol may be more stringent that the ECE R.66 requirement. However, these observations are for buses that are over fifteen years old and may not be applicable to the current U.S. fleet.

EMERGENCY EVACUATION STUDY

Several safety recommendations from the National Transportation Safety Board (NTSB) concern egress, emergency exit designs, lighting and signage/marking for motorcoaches (intercity buses). Conducting egress testing to evaluate motorcoach emergency evacuation designs under various post-incident conditions such as fire, smoke and unusable exit situations is also included in the NTSB recommendations.

Research Plan

NHTSA developed a research plan that is being conducted by the Volpe National Transportation System Center. The approach included the following general areas of investigation or activity: 1) Literature review to identify and evaluate relevant studies, modeling efforts, and regulations and standards from other transportation modes (e.g., rail and air) for applicability to motorcoaches, 2) survey and evaluation of various motorcoach emergency egress designs, including signage and marking, 3) conducting controlled evacuation simulations and egress experiments under various conditions and from various types of emergency exits, 4) measure and evaluate emergency exit opening force requirements, and 5) examine performance requirements for FMVSS No. 217 concerning exit opening force levels, signage, marking and lighting.

Preliminary Findings

Pilot studies [Volpe, 2008] have been completed for front door, emergency window, roof hatch, and wheel chair access door egress tests in addition to naturalistic observations of motorcoach egress of passengers. In addition, emergency window exit opening force measurements were made on three different models of motorcoaches (Prevost, Van Hool, MCI).

Some of the preliminary findings [NHTSA, 2009] from the testing and literature review are: the front access door of the motorcoach is the fastest and safest path of egress; the time required for passengers to determine how to open the front access door (in those cases where the motorcoach operator is unavailable) can take longer than the time required for a full load of passengers to evacuate through the door; conspicuous placement of the service door interior release mechanism and operational instructions are critical for passengers; able-bodied bus passengers are capable of egressing through a rear side door without steps (such as a wheel chair access door) at a rate that would allow evacuation of a fully loaded motorcoach in less than three minutes; the time to evacuate a fully loaded motorcoach through emergency exit windows is less than two minutes provided that passengers have the strength and agility to open the windows and climb out, and if methods of holding the windows open are available as shown in Figure 7.

Figure 7. Window Emergency Egress with Support Mechanism

Based upon the results of the pilot studies, construction of a motorcoach mockup for further egress assessment has been initiated for completion in 2009. The additional investigation will include the following general areas of investigation or activity: 1) motorcoach egress under adverse conditions (e.g., darkness); 2) human factors evaluation of egress using alternative options including seated jump and controlled drop from an elevated platform simulating the floor height for wheelchair access door, and a steep rear stairway similar to those used in European motorcoaches; 3) measurement of human strength in applying opening forces in the specific postures required in motorcoaches;
4) experimental determination of the effect of illumination levels on egress rates; and
5) development of performance requirements including interior egress, vehicle safety aids and emergency lighting.

FIRE SAFETY EFFORTS

While motorcoach fires may be relatively rare, they can cause a significant number of fatal or serious injuries during a single event.
Based upon the investigation of the Wilmer, Texas bus fire, it is evident that the fire originated from outside the vehicle cabin due to overheating of a vehicle axle. Additionally, the motorcoach recall data and industry studies indicate that most motorcoach fires start in areas external to the passenger compartment. It is rarely reported that fires start within the passenger compartment.

Of the fires that originate from outside the vehicle cabin, most originate in one of four areas: the engine compartment, the fuel system, the electrical system, or the wheel well. [NFPA, 2006] Causes of these fires range from mechanical failures of the equipment to leaks in hoses, couplings, seals and electrical circuit shorts.

Because numerous fire safety tests and standards already exist, NHTSA's approach is to build upon existing standards and recommended practices rather than develop new test procedures for materials used in construction of motorcoaches. NHTSA's approach also includes potential improvements to motorcoach performance requirements to address fires that originate both within the passenger compartment and those ignited external to it. Resistance to fire propagation is a key component to preventing burn and inhalation injuries, which were identified as the leading cause of death in fires that primarily originate from sources outside the vehicle cabin. Additionally, low flammability of interior components helps provide additional time for motorcoach occupants to evacuate a burning motorcoach and operators to suppress small fires that begin inside the cabin [NBSIR, 1978].

To evaluate potential fire protection tests and standards for relevancy to improving motorcoach safety, NHTSA initiated a research program with the National Institute of Standards and Technology (NIST) to establish an understanding of the development of motorcoach fires and the subsequent spread into the passenger compartment, assess the adequacy of the current FMVSS No. 302 for flammability testing of interior materials for motorcoach applications, recommend potential upgrades to the existing FMVSS No. 302 requirements, determine the feasibility of establishing requirements for fire-hardening or fire resistance of motorcoach exterior components, assess the potential for fire and smoke inhalation injuries to occupants in the event of a motorcoach fire, and identify potential mitigation strategies.

NIST is using the rear section of the motorcoach crash tested in December 2007 to create a mock-up for conducting controlled burn experiments that mimic fires originating in the wheel well area. These mock-up studies will be conducted in two phases. During the initial testing phase, the cabin will be instrumented with thermocouples, calorimeters, and video equipment to ascertain the effects of such fires on the passenger compartment. The tests will record the rate of fire growth, cabin environmental conditions, and cabin visibility vs. time for each ignition source. During the second phase of testing, various potential countermeasures (firewalls, temperature sensors, etc.) will be selected and tested to determine the extent to which each countermeasure improves the detection time, or potential evacuation time allowable for each ignition source.

CONCLUSION

While motorcoach travel in the United States is already very safe, NHTSA has been actively researching ways to improve bus safety for several years. The agency has recently launched a comprehensive program to improve motorcoach safety in a number of priority areas. The priority areas being pursued are seat belts to reduce passenger ejection, roof strength, fire safety, and emergency evacuation. The results of these studies will provide a basis for future NHTSA direction to promote additional improvements for motorcoach occupant protection.

REFERENCES

Motorcoach Fire on Interstate 45
During Hurricane Rita Evacuation
Near Wilmer, Texas, September 23, 2005; NTSB/HAR-07/01; National Transportation Safety Board, February 2007.

Docket No. NHTSA-2007-28793, 2007.

NHTSA Vehicle Crash Test Database, http://www-nrd.nhtsa.dot.gov/database/veh/veh.htm

NHTSA, "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems-II," Docket No. NHTSA-1999-6407-0005, 1999

Motor Coach Glazing Retention Test Development for Occupant Impact During a Rollover, August 2006, Docket No. NHTSA-2002-11876-15.

Human Factors Issues in Motorcoach Emergency Egress, August 14, 2008, John A. Volpe National Transportation System Center.

NHTSA Interim Report, "Human Factors issues in Motorcoach Emergency Egress", To be published, 2009.

"Vehicle Fires Involving Buses and School Buses," National Fire Protection Association; 2006.

National Institutes for Science and Technology Report NBSIR 78-1421, March 1978.

National Institutes for Science and Technology Report NISTIR 6563, April 2004.

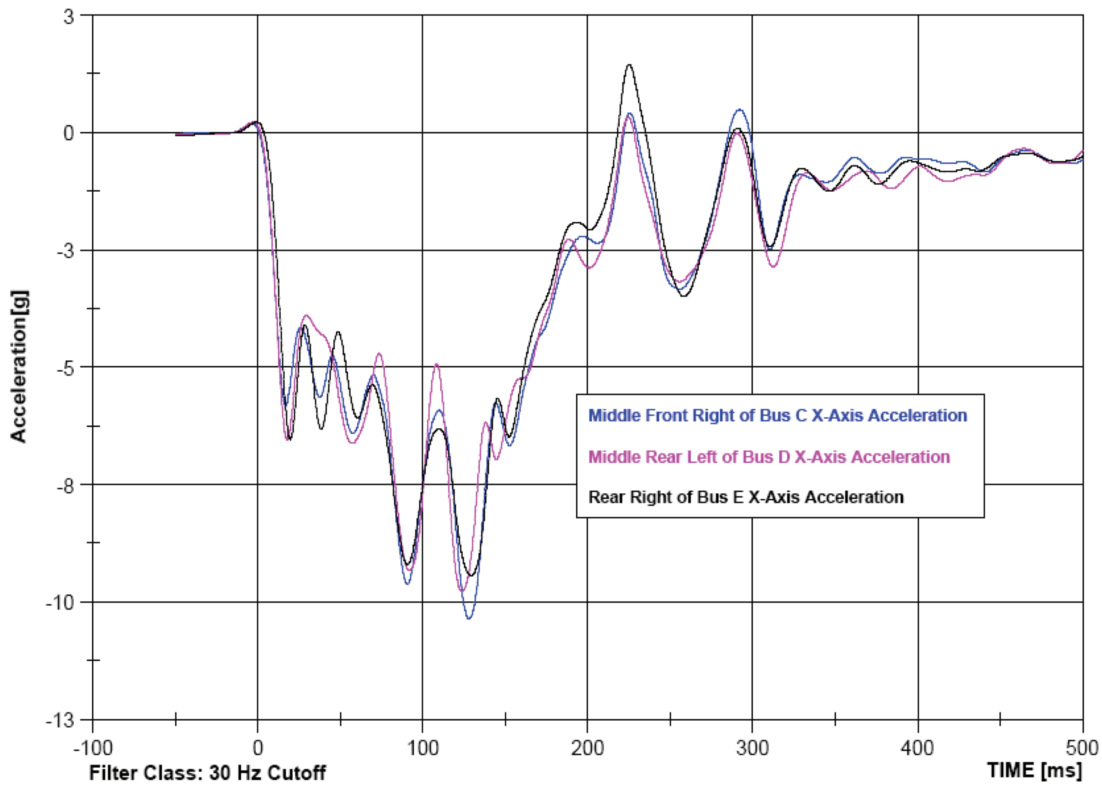

Figure A1. Motorcoach Crash Pulse

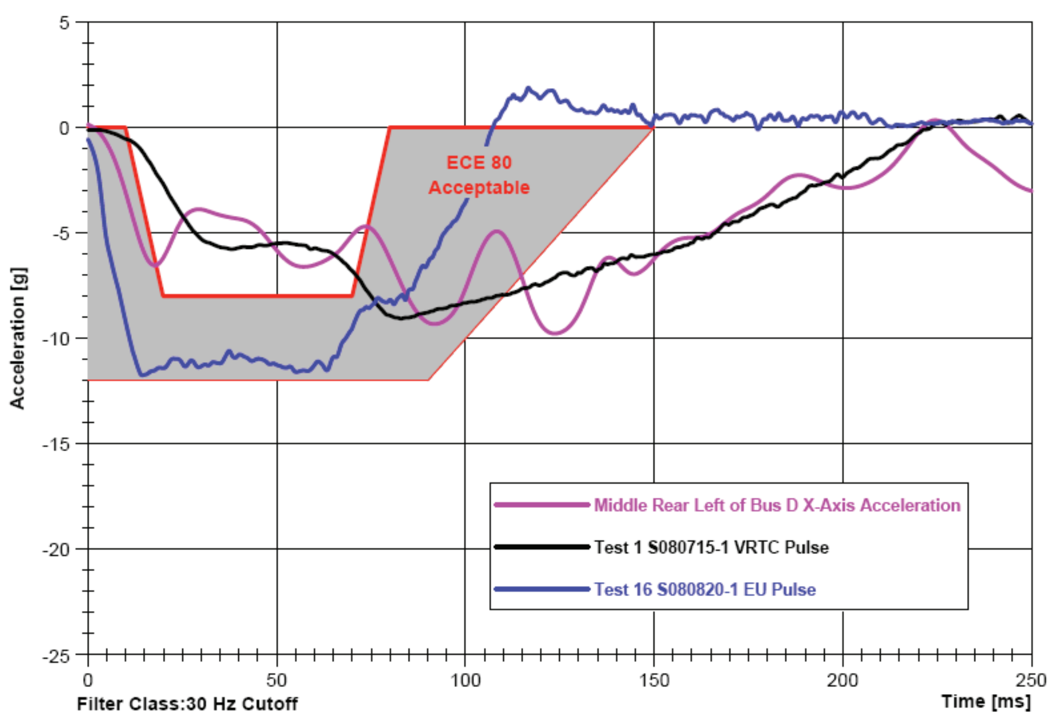

Figure A2. Accelerations for Crash Test (magenta), NHTSA Sled Pulse (black) and EU Pulse (blue)

STUDY ON VISIBILITY AND DISCOMFORT GLARE OF ADAPTIVE FRONT LIGHTING SYSTEM (AFS) FOR MOTORCYCLES

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ABSTRACT

When a motorcycle is driven on a curved road, the motorcycle headlamp inclines horizontally as the motorcycle body banks, and the area illuminated by the headlamp becomes limited. Therefore, minimizing the horizontal inclination of the headlamp would improve the visibility.
This study was conducted to clarify the effects of a system to adjust the horizontal inclination of the motorcycle headlamp (hereafter, “motorcycle AFS”) on visibility for the rider, and to examine the side-effects of the motorcycle AFS (e.g., discomfort glare for oncoming drivers).
The study included the following two parts:
(1) A simulation survey and an actual driving survey to test the visibility demonstrated that a motorcycle AFS enhances visibility for the rider while the motorcycle is being driven on curved road. When the horizontal inclination of the headlamp is adjusted by the same or greater amount than the bank angle of the motorcycle body, the visibility evaluation scores are equal to or above the just acceptable level. However, when the adjustment amount is less than the bank angle, the visibility evaluation scores are below the just acceptable level.
(2) A simulation survey and an actual driving survey to evaluate the discomfort glare showed that when the horizontal inclination of the headlamp is adjusted by the same or smaller amount than the bank angle, the glare evaluation scores are equal to or above the just acceptable level. However, when the adjustment amount is more than the bank angle, the glare evaluation scores are below the just acceptable level.

Based on the results obtained in this study, the following technical requirement is proposed for the motorcycle AFS:
"A horizontal inclination adjustment system (HIAS) may be installed. However, the adjustment amount of horizontal inclination shall not exceed the vehicle's bank angle."

INTRODUCTION

In recent years, adaptive front lighting systems (AFS) have been increasingly introduced for four-wheeled vehicles. The AFS is designed to improve the visibility for the driver in accordance with the driving conditions by controlling the optical axis of headlamps in coordination with steering wheel operation and/or by using a supplementary light source in addition to existing headlamps.
With regard to the motorcycle AFS, Japanese motorcycle manufacturers have presented AFS-mounted prototype vehicles as part of the Advanced Safety Vehicle (ASV) Project, which is being implemented by Japan’s Ministry of Land, Infrastructure and Transport. However, the motorcycle AFS has not yet been released.
In the case of a motorcycle headlamp, when a motorcycle is driven on a curved road, the motorcycle headlamp inclines horizontally as the vehicle body banks, and the area illuminated by the headlamp becomes limited. The range of road illuminated by the headlamp in the direction of travel tends to become narrow because the headlamp horizontally inclines with the vehicle body in curves.

Therefore, the visibility could be improved if the horizontal inclination angle of the headlamp (hereafter, "inclination angle") could be adjusted to keep the cut-off line horizontal (Figure 1). In order to obtain the data required to draw up motorcycle AFS regulations, this study examined the effect of inclination angle on improving the visibility for riders and on the discomfort glare for oncoming vehicle drivers.

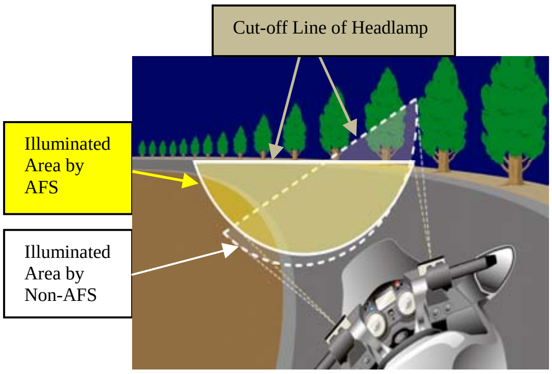

Figure 1. Illuminated area by AFS headlamp and non-AFS headlamp

MEASUREMENT OF THE INCLINATION ANGLE AND THE AIMING DIRECTION OF A MOTORCYCLE HEADLAMP IN A CURVE

Objective

The objective of this research item was to measure the inclination angle and the aiming direction of a motorcycle headlamp in a curve.

Method

Test Vehicle and CCD Cameras - The test vehicle was a 400 cc class motorcycle fitted with a CCD camera at the usual headlamp position (850 mm above the ground). The images taken by the onboard camera (Figure 2) and the images taken by the CCD camera fixed on the ground (Figure 3) were analyzed to determine the inclination angle and the aiming direction of the motorcycle headlamp. These two images were synchronized by LED lamps.

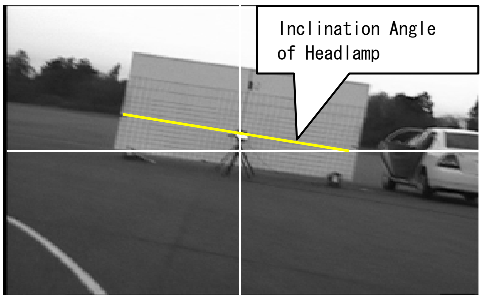

Figure 2. Image by motorcycle mounted CCD camera

Figure 3. Image by CCD camera fixed on the ground

Test Course - While a motorcycle was driven counterclockwise around a circular test track (marked with white lines of different radii; see Figure 4), the inclination angle and the aiming direction of the motorcycle headlamp in a left curve were measured.

Figure 4. Test course (circular test track)

Measurement Conditions - Four radii of lane curvature were used: 30 m, 50 m, 70 m and 140 m.
The vehicle speeds were determined by the method for calculating minimum radii in "Interpretation and implementation of the road construction ordinance [1]."

Test Riders - The test riders were four males who frequently rode motorcycles for test work.

Number of Measurements - The measurements were taken 20 times under each measurement condition (4 riders x 5 runs).

Results

Based on the analysis results of the 20 rounds for each measurement condition, the median values of the inclination angle of the motorcycle headlamp and the aiming direction for that inclination angle were obtained as shown in Table 1.

Table 1. Results of headlamp inclination angle and aiming direction measurement

Radius	Vehicle Speed	Headlamp		
		Inclination Angle	Aiming Direction (Degree)	
			Y	Z
30m	30km/h	12.9°	1.7	0.3
50m	40km/h	13.3°	3.6	0.2
70m	50km/h	15.2°	0.5	0.2
140m	60km/h	13.4°	1.3	0.4

Y : + Indicates rightward. Z : + Indicates upward.

SIMULATION SURVEY ON VISIBILITY OF MOTORCYCLE AFS

Objective

The objective of this computer simulation was to compare visibility performance among headlamps with fixed inclination angle adjustment, a headlamp whose cut-off line was adjusted to remain parallel to the ground at all times (AFS headlamp), and a conventional headlamp.

Method

Visual targets were assumed to be visible by the rider if they were located below the cut-off line of the motorcycle headlamp's passing beam (i.e. within the reach of intense headlamp light). Therefore the visibility distance was determined based on the criterion that the visual target is considered visible when it is located in the range below the cut-off line of the headlamp.

Headlamps - A simulation was conducted on the headlamp's passing beam presenting a symmetrical lighting pattern with a horizontal cut-off line. The headlamp aiming direction was set with a cut-off line 1% (0.57 degrees) downward of the horizontal.

Simulation Conditions - The simulation was conducted for the condition where the motorcycle headlamp inclination angle was adjusted and for the conditions where the inclination angle was not adjusted. A total of four adjustment conditions were set: three conditions with the fixed inclination angle adjustments (7.5 degrees, 15 degrees and 22.5 degrees) and one condition with the cut-off line adjusted to remain parallel to the ground (AFS headlamp).

Driving Course and Visual Targets - The motorcycle driving course and the visual targets are shown in Figure 5. The lane width was 3.5 m, and the motorcycle was driven along the center of the left lane on a left curve. The distance was indicated based on the circular distance along the lane center.
Four radii of lane curvatures were used: 30 m, 50 m, 70 m and 140 m.
Three visual targets were set: lane edge line, lane center, and center line in the left curve.

Range of Calculation - The range of calculation was determined to be that where the distance between the motorcycle headlamp location and the visual target reaches 1/4 of the circle or 100 m. That is, the calculation was performed using the 47 m range for the radius of 30 m, the 78 m range for the radius of 50 m, and the 100 m range for the radii of 70 m and 100 m.

Input Data - The input data necessary for the calculation (the inclination angle and the aiming direction of the motorcycle headlamp) as shown in Table 1 were used.

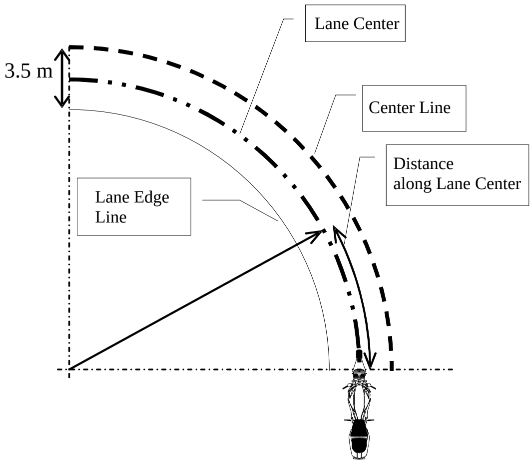

Figure 5. Driving course and visual targets

Results

The results of simulating motorcycle AFS visibility are shown in Table 2.
The ground angle is indicated as negative when the inclination angle adjustment of the motorcycle headlamp is smaller than the bank angle of the vehicle body, as zero when they are equal, and as positive when the inclination angle adjustment is larger (hereafter the same applies).
Compared with the case in which the inclination angle is not adjusted (= 0 degree), the cut-off line reaching distance becomes longer when the inclination angle is adjusted.
When the inclination angle adjustment is 22.5 degrees (with the positive ground angle) and at the AFS condition (with the zero ground angle), all the visual targets are located below the cut-off line.
Assuming that an acceptable visibility distance is 40 m or longer, all the visual targets are within the acceptable range when the inclination angle adjustment is 15 degrees, 22.5 degrees and at the AFS condition.
Consequently, the visibility for the rider is improved by adjusting the headlamp inclination angle in a curve.
In particular, when the adjustment is the same as the bank angle of the vehicle body (with zero ground angle) or higher (with positive ground angle), the visibility is greatly improved.

Table 2. Results of visibility simulation for headlamp inclination angle adjustment (Distance between headlamp and cut-off line : m)

Radius	Vehicle Speed	Headlamp: Inclination Angle Adjustment	Headlamp: Ground Angle (Degree)	Visual Target: Lane Edge	Visual Target: Lane Center	Visual Target: Center Line
30m	30km/h	0°	−12.9	9	13	16
		7.5°	−5.4	19	21	23
		15°	2.1	○	○	○
		22.5°	9.6	○	○	○
		AFS	0	○	○	○
50m	40km/h	0°	−13.3	9	15	18
		7.5°	−5.8	20	23	26
		15°	1.7	○	○	○
		22.5°	9.2	○	○	○
		AFS	0	○	○	○
70m	50km/h	0°	−15.2	11	18	23
		7.5°	−7.7	21	25	29
		15°	−0.2	95	95	94
		22.5°	7.3	○	○	○
		AFS	0	○	○	○
140m	60km/h	0°	−13.4	18	26	33
		7.5°	−5.9	36	41	46
		15°	1.6	○	○	○
		22.5°	9.1	○	○	○
		AFS	0	○	○	○

○ : Indicate all visual targets are below cut-off line.

[shaded] : Indicate cut-off lines are over 40m ahead from headlamp.

ACTUAL DRIVING SURVEY ON VISIBILITY OF MOTORCYCLE AFS

Objective

An actual driving survey was conducted to confirm the results of the computer simulation survey by comparing the visibility performance among headlamps with fixed inclination angle adjustment, a headlamp whose cut-off line was adjusted to remain parallel to the ground at all times (AFS headlamp), and a conventional headlamp.

Method

Test Motorcycles - Two 250 cc class motorcycles, two 400 cc class motorcycles and a 1200 cc class motorcycle were used (Figure 6).

Headlamps - Five motorcycle halogen headlamps conforming to the light distribution requirements for motorcycles (125 cc or more) of ECE R 113 were used. The headlamp heights

were 850 mm above the ground. Passing beams with symmetrical light distributions (horizontal pattern cut-off line) were evaluated.
The following five headlamp conditions were used:
(1) Inclination angle is not adjusted (0 degree)
(2) Fixed inclination angle adjustment of 7.5 degrees
(3) Fixed inclination angle adjustments of 15 degrees
(4) Fixed inclination angle adjustment of 22.5 degrees
(5) Prototype AFS headlamp with the cut-off line adjusted to remain parallel to the ground at all times

(Non-AFS headlamp) **(AFS headlamp)**

Figure 6. Test motorcycles and headlamps

Driving Courses - The circular test track (Figure 4), an urban test road and a middle-speed oval test track were used for the visibility evaluation. The motorcycles were driven counterclockwise around the circular test track. Four radii of lane curvature were used: 30 m, 50 m, 70 m and 140 m.

Driving Methods and Vehicle Speed - Subjects wearing helmets (light transmittance of windshields was around 90%) drove the motorcycles, and were instructed to drive at the following speeds.
(1) Circular test track: Same as Table 1.
(2) Urban test road and middle-speed oval test track: Within the speed limits (maximum speed was 60 km/h).

Headlamp Visibility Evaluation - After each driving, the subjects reported on the headlamp visibility using the following evaluation scale:

1: Inadequate
2: Somewhat inadequate
3: Just acceptable
4: Somewhat adequate
5: Adequate

A value of 3.0 is the "just acceptable" level, so 3.0 or higher means an acceptable or adequate level of visibility.

Subjects - Nine subjects participated in the test on the circular test track, and 8 subjects participated in the test on the urban test road and the middle-speed oval test track. All of them were lamp experts.

Results

The average visibility evaluation values rated by the 9 or 8 subjects are shown in Figures 7 and 8. A significant difference between the evaluation value for when the inclination angle of the headlamp was not adjusted (0 degree) and that when it was adjusted is indicated as * ($p<0.05$) or ** ($p<0.01$).

Visibility Evaluation on a Circular Test Track - The test results on a circular test track are summarized as follows (Figure 7).
(1) The visibility evaluation value is higher when the inclination angle is adjusted or at the AFS condition compared with when the headlamp is not adjusted (0 degree), with a significant difference at all radii.
(2) The visibility evaluation value at the AFS condition is highest.
(3) The visibility evaluation value is higher when the headlamp inclination angle adjustment is bigger.
(4) The visibility evaluation value for the 0 degree condition is below the acceptable borderline of 3.0 at all radii. But the visibility evaluation value for 15 degrees, 22.5 degrees and the AFS condition are within the acceptable range at all radii.

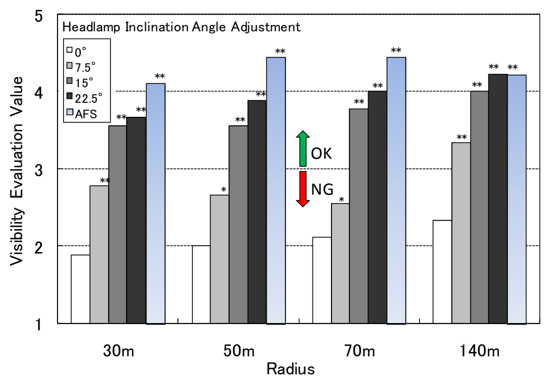

Figure 7. Visibility evaluation on the circular test track

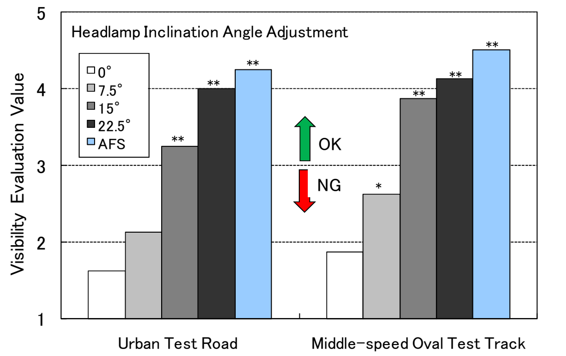

Figure 8. Visibility evaluation on the urban test road and the middle-speed oval test track

Visibility Evaluation on the Urban Test Road and the Middle-speed Oval Test Track - The test results on the urban test road and the middle-speed oval test track are summarized as follows (Figure 8).

(1) Both on the urban test road and the middle-speed oval test track, the visibility evaluation value for 15 degrees, 22.5 degrees and the AFS condition is significantly higher compared with the case in which the inclination angle of the headlamp is not adjusted (0 degree).

(2) Both on the urban test road and the middle-speed oval test track, the visibility evaluation value at the AFS condition is highest.

(3) The visibility evaluation value is higher when the headlamp inclination angle adjustment is bigger.

(4) Both on the urban test road and the middle-speed oval test track, the visibility evaluation values for the 0 degree and 7.5 degree conditions are below the acceptable borderline of 3.0. But the visibility evaluation value for the 15 degrees, 22.5 degrees and AFS conditions are within the acceptable range.

Consequently, it was clarified that the visibility for the rider is improved by adjusting the headlamp inclination angle in a curve.

In particular, the 15 degrees, 22.5 degrees and AFS headlamp conditions greatly improve the visibility in different road conditions.

The results of the computer simulation survey were confirmed by the actual driving survey on headlamp visibility.

SIMULATION SURVEY ON GLARE OF MOTORCYCLE AFS

Objective

The objective of this computer simulation was to compare the glare for the oncoming vehicle driver among headlamps with fixed inclination angle adjustment, a headlamp whose cut-off line is adjusted so that it remains parallel to the ground at all times (AFS headlamp), and a conventional headlamp.

Method

The range of the motorcycle headlamp glare for the oncoming vehicle driver was determined on the criterion that the glare is considered present when the eye location (“eyepoint”) of the oncoming vehicle driver is below the cut-off line of the motorcycle headlamp’s passing beam (that is, when the relatively strong light of the headlamp reaches the eyepoint).

The headlamps, aiming direction and inclination angle adjustment conditions used in the glare simulation are the same as those described in "Simulation survey on visibility of motorcycle AFS".

The input data necessary for the calculation (the inclination angle adjustment and the aiming direction of the headlamp) as shown in Table 1 were used.

Driving Course and Driver Eye Location - The motorcycle driving course and the oncoming car driver's eyepoint location are shown in Figure 9.
The lane width is 3.5 m, and the motorcycle was driven along the center of the left lane on a left curve or right curve. The oncoming vehicle driver's eyepoint location was set at the standard eyepoint location of the drivers of passenger cars driving along the center of the oncoming lane (1.35 m outward from the center line and 1.1 m above ground). The indication of distance and the conditions of radii of curves are the same as those described in "Simulation survey on visibility of motorcycle AFS".

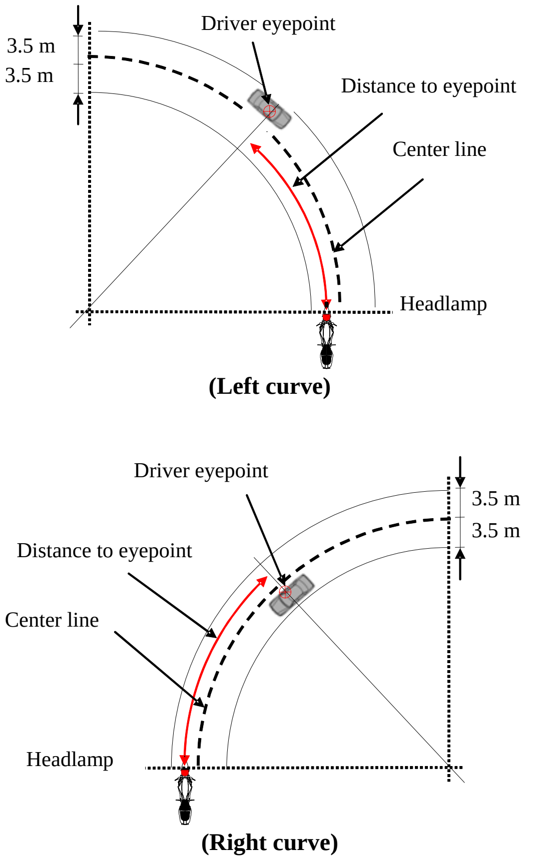

Figure 9. Driving course and driver eyepoint location

Range of Calculation - The range of calculation was determined to be the range where the distance between the motorcycle headlamp location and the eyepoint reaches from 30 m to 1/4 of the circle or from 30 m to 100 m. That is, the calculation was performed using the 30–47 m range for the radius of 30 m, the 30–78 m range for the radius of 50 m, and the 30–100 m range for the radii of 70 m and 100 m.

Results

The results of the simulation of motorcycle AFS glare are given in Table 3. Here, the ranges where the oncoming vehicle driver's eyepoints are below the motorcycle headlamp cut-off line are considered.
The eyepoints are located above the motorcycle headlamp cut-off line without exception when the headlamp inclination angle adjustment is 0 degrees (with the negative ground angle), 7.5 degrees (with the negative ground angle), and at the AFS condition (with the zero ground angle). Therefore, the oncoming vehicle driver receives no glare under all these conditions.
For the 15 degree headlamp inclination angle adjustment, when the ground angle is negative the oncoming vehicle driver receives no glare since the driver eyepoint is above the cut-off line, but when the ground angle is positive the oncoming vehicle driver receives glare since the driver eyepoint is below the cut-off line of headlamp.
For the 22.5 degree headlamp inclination angle adjustment, the ground angle is positive for all radii, and the oncoming vehicle driver receives glare since the driver eyepoint is below the cut-off line of the headlamp.
In summary, the oncoming vehicle driver receives no glare when the headlamp inclination angle is adjusted to the same or lower level as the vehicle body bank angle, but does receive glare when it is adjusted to a higher level.

Table 3. Results of glare simulation for headlamp inclination angle adjustment (Range where driver eyepoints are below cut-off line: m)

Radius	Vehicle Speed	Headlamp Inclination Angle	Headlamp Ground Angle (Degree)	Curve Left Curve	Curve Right Curve
30m	30km/h	0°	−12.9	○	○
		7.5°	−5.4	○	○
		15°	2.1	35～47	30～47
		22.5°	9.6	30～47	30～47
		AFS	0	○	○
50m	40km/h	0°	−13.3	○	○
		7.5°	−5.8	○	○
		15°	1.7	56～78	50～78
		22.5°	9.2	30～78	30～78
		AFS	0	○	○
70m	50km/h	0°	−15.2	○	○
		7.5°	−7.7	○	○
		15°	−0.2	○	○
		22.5°	7.3	33～100	30～100
		AFS	0	○	○
140m	60km/h	0°	−13.4	○	○
		7.5°	−5.9	○	○
		15°	1.6	○	○
		22.5°	9.1	47～100	30～100
		AFS	0	○	○

○ : Indicate driver eyepoints are always above cut-off line.

x～y : Indicate the range (m) where eyepoints are below cut-off line.

ACTUAL DRIVING SURVEY ON GLARE OF MOTORCYCLE AFS

Objective

The objective of this actual driving survey was to confirm the results of the computer simulation survey comparing glare for the oncoming vehicle driver among headlamps with fixed inclination angle adjustment, a headlamp whose cut-off line is adjusted so that it remains parallel to the ground at all times (AFS headlamp), and a conventional headlamp.

Method

Test Motorcycles and Headlamps - The test motorcycles and headlamps used in this survey are the same as those in "Actual driving survey on visibility of motorcycle AFS".

Driving Course - The middle-speed oval test track was used for glare evaluation. Motorcycles were driven clockwise on a right curve of radius 180 m (Figure 9).

Evaluation Method and Vehicle Speed - Subjects in the driver seat of the stationary car were instructed to look ahead and to evaluate the glare of the oncoming motorcycle headlamp. The observation was performed between 100 m and 30 m ahead from the driver eyepoint.

Headlamp Glare Evaluation - After each driving, subjects reported on headlamp glare using the following De Boer's 9-point scale, which is widely used for evaluating discomfort glare:

1: Unbearable glare
2:
3: Glare obstructing driving
4:
5: Permissible maximum glare (just acceptable)
6:
7: Fully permissible glare
6:
9: No perception of glare

A value of 5.0 is the "just acceptable" level, so 5.0 or higher means an acceptable or adequate level of glare.

Subjects - A total of 8 subjects participated. All of them were lamp experts.

Results

The average glare evaluation values rated by the 8 subjects are shown in Figure 10.
A significant difference between the evaluation value for the condition in which the inclination angle of the headlamp is not adjusted (0 degree) and for the condition in which the inclination angle is adjusted is indicated as * ($p<0.05$) or ** ($p<0.01$).
The test results are summarized as follows.
(1) Compared with the case in which the inclination angle of the motorcycle headlamp is not adjusted (0 degree), the glare evaluation value is significantly lower when the inclination angle is adjusted to 7.5 degrees, 15 degrees and 22.5 degrees.
(2) The glare evaluation value is lower when the headlamp inclination angle adjustment is bigger.
(3) The glare evaluation value for the 0 degree, 7.5 degrees and AFS condition is within the

acceptable range, but the glare evaluation values for 15 degrees and 22.5 degrees are below the acceptable level. In this driving situation (on a curve of radius 180 m at 60 km/h), the bank angle of the motorcycle body is estimated to be 13 degrees. Therefore, for the 15 degrees and 22.5 degrees conditions, the headlamp inclination angle adjustment exceeds the bank angle of the vehicle body (with the positive ground angle),

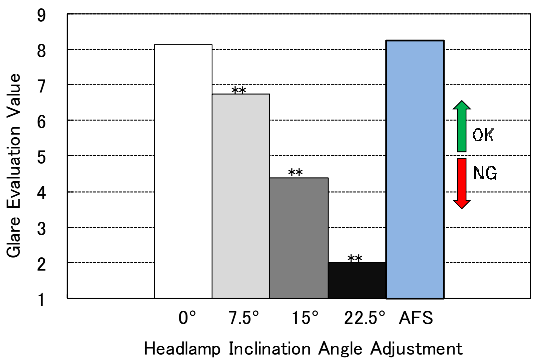

Figure 10. Glare evaluation for headlamp inclination angle adjustment

Hence, the oncoming vehicle driver receives glare within the acceptable range when the headlamp inclination angle is adjusted to the same or lower level as the vehicle body bank angle, but does receive unacceptable glare when it is adjusted to the level higher than the vehicle body bank angle.

CONCLUSION

The results obtained in the "Simulation survey on visibility of motorcycle AFS" and "Simulation survey on glare of motorcycle AFS" are summarized in Table 4.
In the visibility evaluation, it is assumed that visibility is acceptable if the cut-off line of the headlamp light reaches 40 m or longer forward at the lane edge line.
In the glare evaluation, it is assumed that oncoming vehicle drivers receive no glare when their eyepoints are located above the headlamp cut-off line.

In the overall synthetic evaluation of the motorcycle headlamp performance in curves, it is deemed satisfactory if both visibility and glare are satisfied.
The results of the study on the motorcycle AFS visibility and glare are summarized as follows:
(1) It was found that the headlamp visibility is improved by adjusting the headlamp inclination angle in curves. The motorcycle headlamp visibility in curves was found to be within the acceptable range when the headlamp inclination angle is adjusted to equal the vehicle body bank angle (with the zero ground angle) or to the level higher than the vehicle body bank angle (with the positive ground angle).
(2) It was found that the oncoming vehicle driver receives no glare when the headlamp inclination angle is adjusted to equal the vehicle body bank angle (with the zero ground angle) or less (with the negative ground angle), but does receive glare when adjusted to more than the vehicle body bank angle (with the positive ground angle).
(3) The overall synthetic evaluation of motorcycle AFS visibility and glare showed that, if the motorcycle headlamp inclination angle is adjusted in curves, it will be appropriate to use an adjustment angle that is close to the vehicle body bank angle but does not exceed it.

Table 4. Summary of visibility evaluation, glare evaluation and overall synthetic evaluation for motorcycle AFS

Radius	Vehicle Speed	Motorcycle Headlamp		Evaluation		
		Inclination Angle Adjustment	Ground Angle (Degree)	Visibiliy	Glare	Synthetic Evaluation
30m	30km/h	0°	−12.9		○	
		7.5°	−5.4		○	
		15°	2.1	○		
		22.5°	9.6	○		
		AFS	0	○	○	○
50m	40km/h	0°	−13.3		○	
		7.5°	−5.8		○	
		15°	1.7	○		
		22.5°	9.2	○		
		AFS	0	○	○	○
70m	50km/h	0°	−15.2		○	
		7.5°	−7.7		○	
		15°	−0.2	○	○	○
		22.5°	7.3	○		
		AFS	0	○	○	○
140m	60km/h	0°	−13.4		○	
		7.5°	−5.9		○	
		15°	1.6	○	○	○
		22.5°	9.1	○		
		AFS	0	○	○	○

○ : Indicate evaluation value is equal to or above just acceptable level.

Indicate evaluation value is below just acceptable level.

Furthermore, the validity of the results of the “Simulation survey on visibility of motorcycle AFS” and “Simulation survey on glare of motorcycle AFS” was also confirmed in the actual driving tests using the motorcycles with the inclination angle adjusted headlamps, a motorcycle with the prototype AFS headlamp and a motorcycle equipped with the conventional headlamp.

REQUIREMENT

Based on the results obtained in this study, the following technical requirement is proposed for the motorcycle AFS:
"A horizontal inclination adjustment system (HIAS) may be installed. However, the adjustment amount of horizontal inclination shall not exceed the vehicle's bank angle."

The formal document submitted to GRE by the expert from Japan proposed the amendment to Regulation No. 53 in order to introduce the requirements concerning the the vehicle's horizontal inclination angle adjustment-type headlamps installed on motorcycles [2].

REFERENCES

[1] Japan Road Association. 2004. "Interpretation and Implementation of the Road Construction Ordinance," pp. 309-320.

[2] ECE/TRANS/WP.29/2009/4. January 2009. "Visibility of adaptive front-lighting system (AFS) for motorcycles and glare, Proposal for Supplement 11 to the 01 series of amendments to Regulation No. 53, Submitted by the expert from Japan".

EFFECTIVENESS EVALUATION OF ANTILOCK BRAKE SYSTEMS (ABS) FOR MOTORCYCLES IN REAL-WORLD ACCIDENT SCENARIOS

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ABSTRACT

Although motorcycle ABS is meanwhile well established on the public market, detailed investigations about the relationship between crash scenarios and the effectiveness of motorcycle-ABS are rare.
Within the EC-funded SIM Project (Safety In Motion) a detailed analysis of different accident scenarios with PTWs (Powered Two Wheelers) has been performed, using the DEKRA PTW-database. The basis of this data pool is the accumulation of written expert opinions containing the accident analyses that are drawn up by skilled forensic experts throughout Germany. From this database containing 350 real-world accidents, 51 cases have been selected by imposing a reaction demand and a following braking of the motorcycle rider in order to evaluate the benefit of advanced brake control systems. The following parameters have been extracted for the evaluation:

- Collision speed and initial speed
- Distance of falling location to collision point
- Braking distance
- Median braking deceleration
- Starting point of breaking
- Reaction point/demand
- Kind of reaction
- Road surface
- Weather

With this information several real accident scenarios without ABS were analysed under the condition that an ABS system would have been installed on the motorbike. With such an approach the difference in the accident consequences with and without ABS can be observed. In addition a variation in the ABS control has been accomplished by considering different brake control systems developed by CONTI, like partial and full integral brake systems as well as systems with advanced driver-assistance functions (ADAS). As a result, a tremendous reduction in the accident consequences can be shown, for example up to 50% of the selected accidents could have been avoided by a simple 2 channel ABS.

INTRODUCTION

Within the EC-funded SIM Project (Safety In Motion) active and passive safety components are studied in PTWs (Powered Two Wheelers) to demonstrate possible improvements in accident avoidance and mitigation.
In order to evaluate the possible benefits of CONTI active safety components, especially ABS, but also integral-brake, brake-assist and advanced driver-assist systems (ADAS), several real accident cases provided by DEKRA were studied. The fundamental basis of the DEKRA accident databases is the accumulation of written expert opinions containing the accident analyses that are drawn up by skilled forensic experts at the DEKRA branches throughout Germany and totalling about 28,000 annually. The particular feature of these reports is that normally the experts are called by the police or prosecuting attorney to come to the accident scene directly after the accident happened. The DEKRA experts operate all over Germany on a 24hour/7day week basis. Consequently, the nearly 500 DEKRA accident experts have the opportunity to acquire all the information necessary for their task. The reports provide a substantial basis for accident research work. The DEKRA Accident Research department has the opportunity to select and analyse interesting cases, which normally consist of the written expert opinions, detailed accident reconstructions, sketches and photo material. The actual DEKRA PTW database comprises 350 cases from 1996 to 2007 with all kinds of other vehicles as well as single PTW accidents. About 300 parameters per accident are reviewed when using the DEKRA questionnaires. Since expert opinions are normally commissioned only

when the accident is of a really serious nature, the main focus of the PTW database is directed towards accidents resulting in severely- or fatally injured persons. These accidents happen mostly in rural areas and involve elevated driving speeds.

In each accident case, one PTW is involved. In almost all cases the reason for the accident seems to be, that a car driver couldn't estimate the speed of the PTW correctly or didn't recognise the PTW in time.
In several cases we can watch the standard situation, where a car driver intends to drive a U-turn without taking notice of a PTW approaching from behind.
As an example of this, fig. 1 shows an original crash photo and fig. 2 an according sketch of the whole accident situation, both provided by DEKRA accident database.

Figure 1. Crash photo of PTW and U-turning car (DEKRA accident database)

Another class of severe accident situations results from car drivers turning into a road without giving way to PTWs driving on this road with considerable speed.
In all these collision cases, the speed of the involved car is rather low, and the severity of the impact just depends on the speed of the PTW, which usually crashes into the car.
Normally the speed of the PTWs was not above the allowed speed limit, so that the PTW drivers behaved correctly.
On the contrary the accidents were in almost all cases caused by the erroneous behaviour of the involved car drivers, who were not able to evaluate the traffic situation properly.

Nevertheless the severe injuries and big damages result from the low medium deceleration of the PTWs, as we can learn from the accident database.

In about 43% of the studied cases, the braked PTW gets unstable (due to overbraking) and hits the ground before the collision with the car occurs.

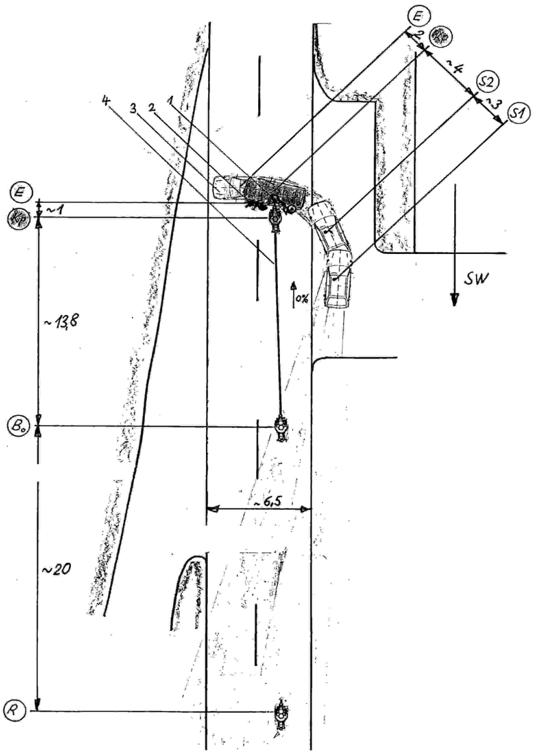


Figure 2. Sketch of the accident situation of figure 1 (DEKRA accident database)

The task of the CONTI investigation described on the following pages is to make an estimation, in which way the effects of all those real accidents could have been mitigated with the help of different electronic brake control systems.

Electronic brake-control devices for collision mitigation

First of all, even a standard ABS should reduce the effects of PTW accidents considerably, providing braking stability for the PTWs on one hand, so that falls can be avoided and the PTWs remain in a manoeuvrable state, and on the other hand increasing braking deceleration due to adjusting operating points just near the friction optimum.
Furthermore, a so-called integral brake can be very much of help in case of panic braking. A PTW driver may focus only on one brake lever during an emergency case, because he is shocked by the suddenness of the situation. It may be impossible then to manage two separate brake levers in an adequate manner simultaneously. In those cases the integral brake adjusts balanced pressure amounts to both wheels, even if the driver

applies only one brake lever.
In addition, a brake-assist function can improve the first pressure build-up time interval just after the first reaction of the PTW driver, which results in applying the brake(s) with a high pressure increase gradient. It's very important then to reach the optimal braking point in short time, in order to achieve the shortest possible braking distance. But investigations of panic-brake situations show us, that a normal driver indeed applies the brake with a high gradient but often releases it a little before the locking pressure of the wheel is reached. The brake-assist function recognises those patterns of behaviour and applies the maximum pressure to the wheels, so that the hesitation of a driver is compensated.
Another class of assist-functions is based on environmental sensors, such as infrared, radar and cameras. With the help of those sensors a critical situation may be recognised just at the beginning and valuable reaction time may be saved. Within a few ms the central computer of the assistance system can make a decision how to react properly and may warn the driver and/or get active without any driver request. In order to avoid driver irritations and due to legal restrictions, the system should not perform full braking, but can reduce gas and pre-fill the brakes in time, which may lead to a vehicle deceleration of about 0.3g. This action shows a lot of benefits. First, the vehicle speed is already slightly reduced, when the driver decides to brake. Secondly, the driver gets sooner aware of the severity of the situation, and additionally, the brakes are already pre-filled when the driver takes over, so that the first pressure increase goes much faster.

Data from DEKRA accident database
The accidents described in the DEKRA database are documented with the help of the following data, which had been evaluated by police and crash experts with the help of situation reconstruction methods, such as measuring brake traces and scratches on the road surface:

1. Distance between “obstacle in sight” (reaction demand) and the later collision location:
This is the distance between the PTW and the later collision location, when the PTW driver first recognises that a problem occurs and he is forced to react.

2. Distance between “start of braking” and the later collision location:
This is the distance between the PTW and the later collision location, when the PTW driver has already applied at least one brake, that means at this point the brake is already filled (visible brake traces on the road start at this point).
Unfortunately, from these data we do not know exactly, where and when the driver first started to apply the brake and in which way he applied it. At the first point, he was forced to make a decision and to react, and at the second point, the reaction time interval is already finished.
Between these two points, no vehicle deceleration is considered, although the driver started to apply the brake in that interval. Due to the fact, that we do not know the braking behaviour of the PTW driver exactly, this simplification is unavoidable.

3. Initial speed:
This is the speed of the PTW at the first and still at the second distance point, because no vehicle deceleration is considered in the interval between the two points.

4. Collision speed:
This is the speed with which the PTW crashes into the collision partner.

5. Falling distance:
This is the distance between the falling location and the later collision location.

6. Braking deceleration:
This is the median vehicle deceleration, which occurs between the “start of braking location” (point 2) and the collision or the fall location (if a fall happens).

As further information the road surface type (asphalt or other), weather conditions and the lighting were taken into account.

With the help of the distances and vehicle speed amounts, time diagrams can be created with corresponding time steps and time intervals.
Fig. 3 shows such a time diagram consisting of two parts, where the upper part presents the vehicle velocity and the lower part the wheel brake pressures as functions of the time.

The time step t_obstacle_in_sight corresponds with point 1, time step t_brakes_filled with point 2. Additionally the reaction time step t_reaction is shown, which defines the start of the brake application. This time step is not defined directly in the database, but can only be estimated from other database information.
Normally this time step occurs 0.3 up to 0.5s before the time step 2, where full braking is already in steady state.
For the following calculations, a medium time interval of 0.4s is assumed as time distance

between t_reaction and t_brakes_filled for all studied accident cases.
In fig. 3 three distances are defined, which in sum yield the full stopping distance s (equal to point 1). The distances are the reaction distance s_react, which the PTW passes through without any braking action of the driver, the filling distance s_fill, which the PTW passes through during driver reaction until the brake(s) are filled, and the brake distance s_brake, which the PTW passes through during full braking or sliding (in case of a fall) until the crash occurs.

Normal PTW braking without support of electronic brake components

Furthermore, fig. 3 shows as examples two typical patterns of behaviour of PTW-drivers in panic.
The first one leads to the situation the result of which is shown with the dashed signal lines. The driver first applies the front-wheel brake with high pressure increase gradient, then hesitates a little, and afterwards applies too much brake pressure, which forces the front wheel to locking. The PTW gets unstable, hits the ground and slides towards the crash partner. Although the hard brake application leads to good deceleration results in the first braking interval, the overall deceleration is rather low due to the occurring fall and the sliding.
The second braking behaviour shown in fig. 3 with the continuous signal lines is similar to the first one, but instead of overbraking the PTW, the driver being aware of the danger of wheel locking shows a more careful and hesitating braking behaviour, which leads to a clear underbraking with a bad overall deceleration result [1].

Therefore, in both cases the collision speed is rather high.

The most important problem of braking a PTW with high deceleration is the fact, that a locking front wheel leads to an unavoidable fall in almost all cases. Even if a driver is very much used to full braking and knows his PTW behaviour quite well, it won't be easy for him to find an optimal operating point abruptly in case of a panic situation. This is due to the fact that the wheel-locking pressure level varies considerably with the wheel load (violet lines P_fw_lock in fig. 3), which again is highly depending on the dynamic behaviour of the PTW. So the locking pressure is rather low at first, when the driver performs an extremely hard front-brake application, because almost all PTWs need about 300ms to get the maximum load on the front wheel. Afterwards this full amount of load is reduced regarding to a certain characteristic, which is installed by the spring and damper adjustments. After about 800ms the PTW is in steady state and the locking level remains on a constant value, presumed that the friction between tire and road surface remains constant too. But this friction is also a complex function of several parameters, which cannot be evaluated properly while acting in panic.

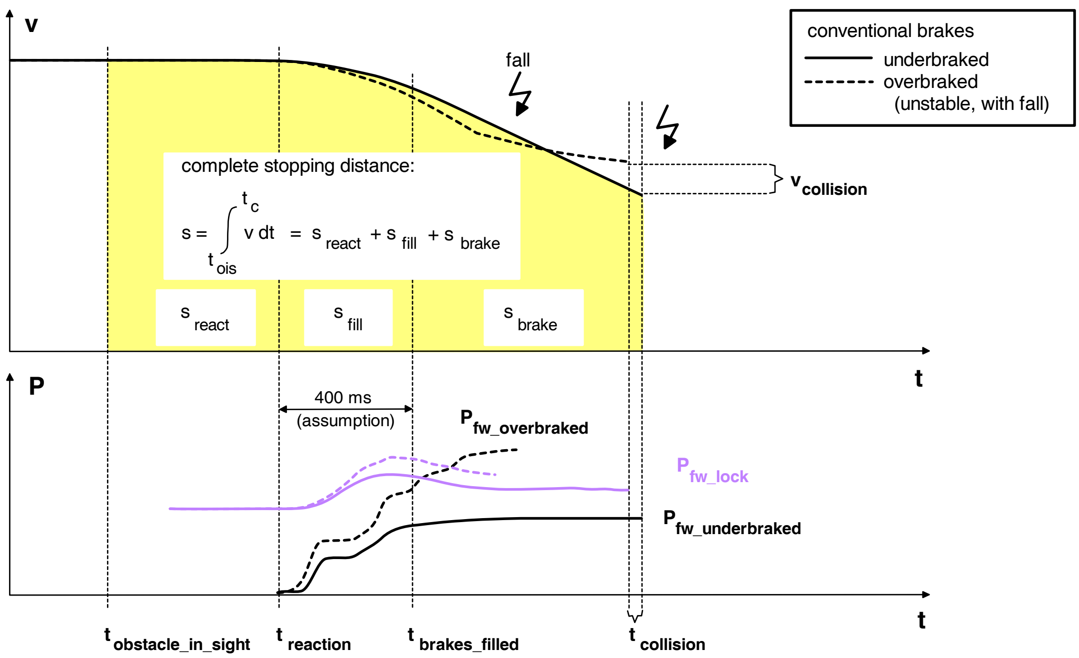


Figure 3. Time diagram of a panic-braking situation without electronic brake control

PTW braking with an ABS control device

Therefore, one of the most important advantages of ABS is that the driver may fully apply the brake levers and can absolutely rely on the optimal slip control with a highly reduced risk of getting unstable. Hesitating and careful braking is no longer necessary. ABS will always limit the wheel pressures to values just below the respective locking pressure line, which is shown in the example of fig. 4. Here, the same dangerous braking situation is presented as in fig. 3, but the braking PTW is assumed to be equipped with ABS. The two lines P_fw_lock (violet) and P_rw_lock (pink) represent the locking-pressure levels of the front and the rear wheel during the braking manoeuvre. The load of the PTW is dynamically transferred from rear to front wheel. With the help of the pressure decrease and increase patterns ABS is always trying to find the wheel-pressure optimum, which is recognised by wheel slip and acceleration observation (recognition mechanism not shown in fig. 4).
In order to demonstrate the benefits of ABS based on the DEKRA accident data, the following assumptions were made (see fig. 4):
In all cases the driver of the respective PTW is considered to behave different now, because he can rely on his electronic brake control system. So it is assumed that he will apply the brake levers harder with the result of filling at least the front brake in just 300ms (compared to the assumed 400ms without ABS).

Unfortunately, another uncertainty has now to be dealt with. Due to the two separated brake actuation levers, we do not know exactly, how the respective driver would have behaved concerning the succession of applying the brake levers.

Therefore, we have to consider three different scenarios:
1. The driver may be extremely shocked by the situation, so that he activates only the front brake. In this case, we assume that the possible vehicle deceleration is not higher than 0.8g.
2. The driver first activates only the front brake and after a short time interval applies the rear brake additionally, so that a medium deceleration of 0.9g is reached in case of highest road friction.
3. The driver is at once fully aware of his brake actuations and applies both levers in parallel. In this case the maximum deceleration is assumed to 1g.

These maximum deceleration values have now to be corrected (reduced) with the help of the road surface and weather information provided by the DEKRA database, because only a dry and warm asphalt or concrete surface enables the PTW to make use of these theoretical values.

The following reductions were considered and taken for the calculation:
1. 95% of the values in case of darkness or cloudy sky.

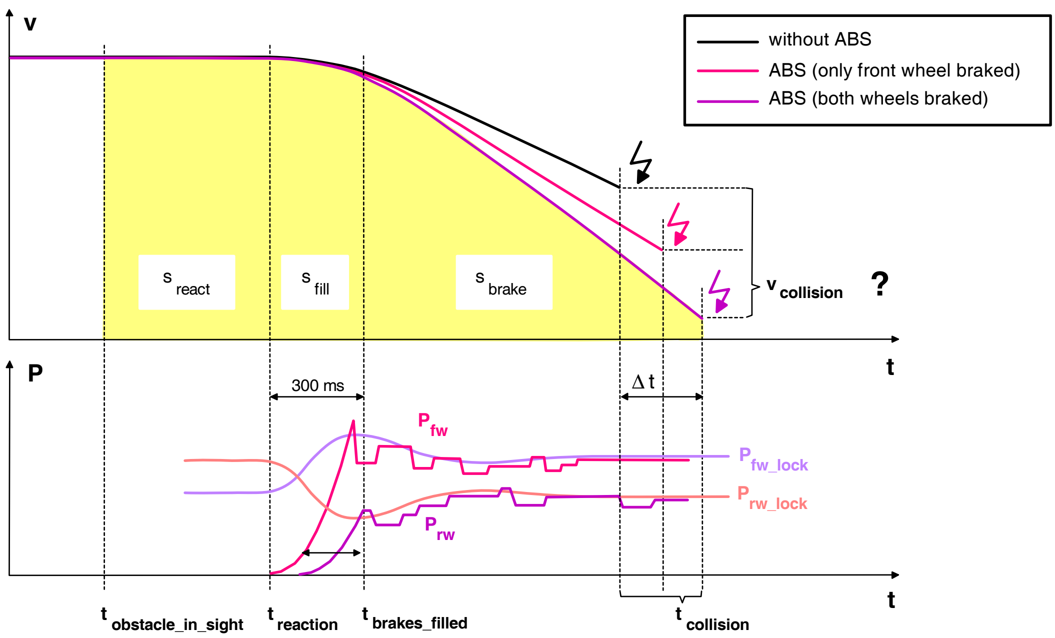


Figure 4. Time diagram of a panic-braking situation with ABS control

2. 90% of the values in case of a wet asphalt surface without heavy rain.
3. 80% of the values in case of heavy rain.
4. 90% of the result in case of slight, 75% in case of considerable and 60% in case of extreme curve braking

Because no other road surfaces and manoeuvres occur in the 51 studied cases and nothing is said about road inclinations, no other reductions had to be made.
Nevertheless it should be mentioned that the deceleration values in reality highly depend on certain technical conditions of the PTW. First of all, good brakes and tires are the most important pre-conditions for maximum braking deceleration. Other devices, like dampers and springs with well adjusted characteristics are very much of help to exploit the maximum friction between tires and road surface. Therefore, networking of electronic control devices can be helpful to make adjustments dynamically according to the respective situation.
With properly working brakes, tires and chassis components more than 10 m/s^2 of braking deceleration are possible on dry asphalt, so that the assumptions made here are in no way too optimistic.

Based on the above assumptions and considering constant circumstances, the following simple calculations can be made to get the expected collision speed and other relevant data for a PTW equipped with properly working ABS:

Available distance for full braking:

$$s\_brake_{ABS} = s\_brake + (0.1s * v\_initial)$$

The values for s_brake and v_initial are the original values from the database.
The 0.1s result from the assumption that the driver will perform a harder brake application with ABS and therefore save at least 0.1s to fill the brake. So the full braking starts 0.1s earlier.
An important remark is necessary here concerning the initial speed of full braking. Strictly speaking, in case of a fast brake application the initial speed would be a little higher than after a slow brake-pressure increase. But in the estimation, this effect can be neglected due to the fact, that without ABS the driver will normally not be able to reach an optimal braking point at all. Due to this effect, an overall time benefit of 0.1s with equal initial speed seems to be realistic when using ABS.

The needed distance for full braking with the above assumed constant deceleration is:

$$s\_brake\_needed_{ABS} = \frac{1}{2} * (v\_initial)^2 / a\_brake_{ABS}$$

If the needed distance $s\_brake\_needed_{ABS}$ is lower than the available distance s_brake_{ABS} no collision would have occurred. Otherwise the collision speed would have been

$$v\_collision_{ABS} = sqrt(2 * a\_brake_{ABS} * (s\_brake\_needed_{ABS} - s\_brake_{ABS}))$$

If a collision had occurred, the time step of the crash would have been delayed by $delta\_T\_c_{ABS}$ compared to the situation without ABS:

$$delta\_T\_c_{ABS} = t\_collision_{ABS} - t\_collision$$

$$t\_collision_{ABS} = t\_brakes\_filled - 0.1s + 2 * s\_brake_{ABS} / (v\_initial + v\_collision_{ABS})$$

$$t\_collision = t\_brakes\_filled + 2 * s\_brake / (v\_initial + v\_collision)$$

→

$$delta\_T\_c_{ABS} = -0.1s + 2 * s\_brake_{ABS} / (v\_initial + v\_collision_{ABS}) - 2 * s\_brake / (v\_initial + v\_collision)$$

In order to get a feeling for the effects of the ABS control, the following example should be looked at (data is based on real accident scenario of DEKRA database):

v_initial = 26 m/s
s_brake = 26 m
v_collision = 19.4 m/s

→

s_brake_{ABS} = 28.6 m
a_brake_{ABS} = 0.9g = 8.83 m/s^2
$s\_brake\_needed_{ABS}$ = 38.28 m
$v\_collision_{ABS}$ = 13 m / s
$delta\_T\_c_{ABS}$ = 0.221 s

So the collision speed would have been reduced by 6.4 m/s, and moreover the driver would have had an additional time interval of 0.221s to react with steering to avoid the obstacle, if possible.
During this time interval a crossing collision partner driving with a speed of 20 kph (5.55 m/s) moves by a distance of 1.23 m, so that it could already be out of way, when the PTW crosses the collision course. This situation is shown by the example in fig. 5.

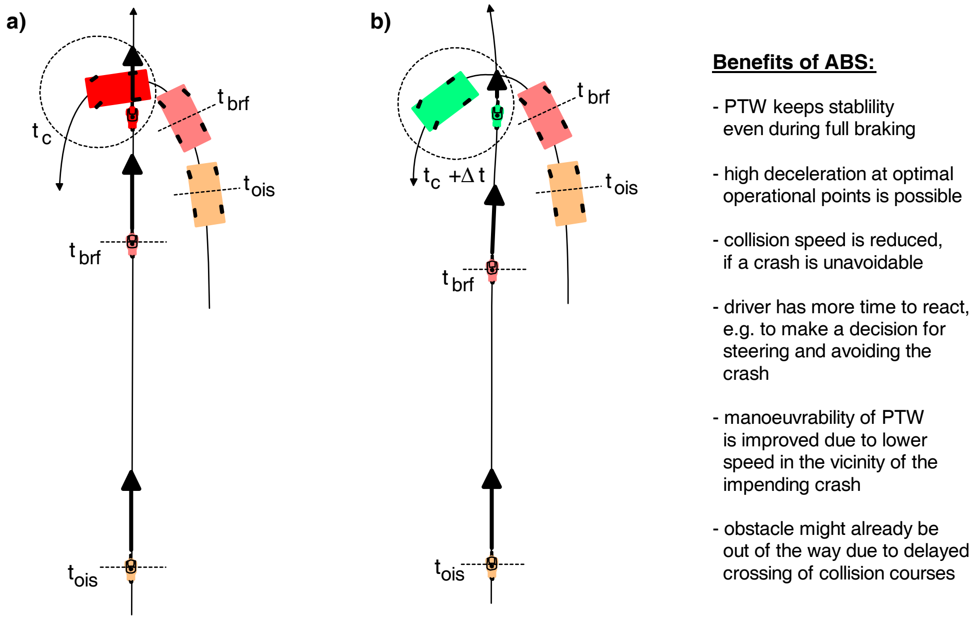


Figure 5. Sketch of a critical driving situation a) with bad, b) with high PTW deceleration

The scenario represents a typical class of severe PTW accidents. A car driver intents to make a U-turn without giving notice to a PTW, which is just going to overtake the car. The corresponding time steps are illustrated by different colours. At time step t_ois (obstacle in sight) the driver of the PTW can first recognise, what the car driver is going to do. So he is forced to react. At time step t_brf (brake filled) he already has reacted with filling the brakes. Time step t_c (collision) represents the time, when the collision actually happens.
As we see from the example, it can be very much of help for the PTW to achieve a brake deceleration, which is just a little increased. The reduced speed in the vicinity of the impending crash location increases the manoeuvrability of the PTW considerably and may enable the driver to avoid the obstacle. Furthermore, he gains an additional time interval delta_T_c $_{ABS}$ (ΔT in fig. 5) for steering action, and the obstacle might have moved already out of the way.
Therefore, it is not sure whether a collision would have happened at all with ABS, even if the theoretical calculation yields a still high collision speed. For this reason the question mark is added to the string “v_collision” in fig. 4.

The benefits resulting from ABS are listed in fig. 5.

PTW braking with ABS control, integral brake and brake-assist function

In the following step the benefits of a so-called integral brake and the brake-assist function are demonstrated (see fig. 6).
When using an integral brake, we can be sure that both wheel-brake circuits will be filled in parallel, so that we always do our calculations with the assumption that a maximum deceleration of 1g is possible on highest friction. For lower friction values, the maximum deceleration is corrected in the same way as above described for the ABS.

The added brake-assist is assumed to have the advantage of filling the brakes always with the highest possible pressure increase gradient. The result shall be a reduced fill time of 200 ms, as shown in fig. 6.
It should be mentioned here, that even shorter pressure increase time intervals are possible with electronic brake devices from CONTI. Due to the adjustment of the orifices of the wheel inlet valves, maximum pressure increase gradients are so high, that the wheel locking-pressure levels can usually be reached within 100ms. But those gradients must be set up by the brake force of the driver and cannot be applied by the ABS pump of the control device alone. For this reason the pressure increase interval is set to the more restrictive value of 200ms. This time interval can be assumed as a medium value, which can be easily achieved by the cooperation of drivers working with medium hand-force and a brake-assist function, which

compensates a certain hesitating during the first brake application.

With these assumptions, the following calculation can be done in a similar manner as above:

Available distance for full braking:

$s\_brake_{INT} = s\_brake + (0.2s * v\_initial)$

The values for s_brake and v_initial are the original values from the database.
The 0.2 s result from the assumption that the brake-filling time with the original initial speed is now reached 0.2 s earlier than with the conventional braking.
Needed distance for full braking with the above assumed deceleration:

$s\_brake\_needed_{INT}$
$= ½ * (v\_initial)^2 / a\_brake_{INT}$

If the needed distance $s\_brake\_needed_{INT}$ is lower than the available distance s_brake_{INT} no collision would have occurred. Otherwise the collision speed would have been

$v\_collision_{INT} = sqrt(2 * a\_brake_{INT} * (s\_brake\_needed_{INT} - s\_brake_{INT}))$

If a collision had occurred, the time step of the crash would have been delayed by $delta\_T\_c_{INT}$ compared to the situation without ABS:

$delta\_T\_c_{INT} = t\_collision_{INT} - t\_collision$

$t\_collision_{INT} = t\_brakes\_filled - 0.2s$
$+ 2 * s\_brake_{INT} / (v\_initial + v\_collision_{INT})$

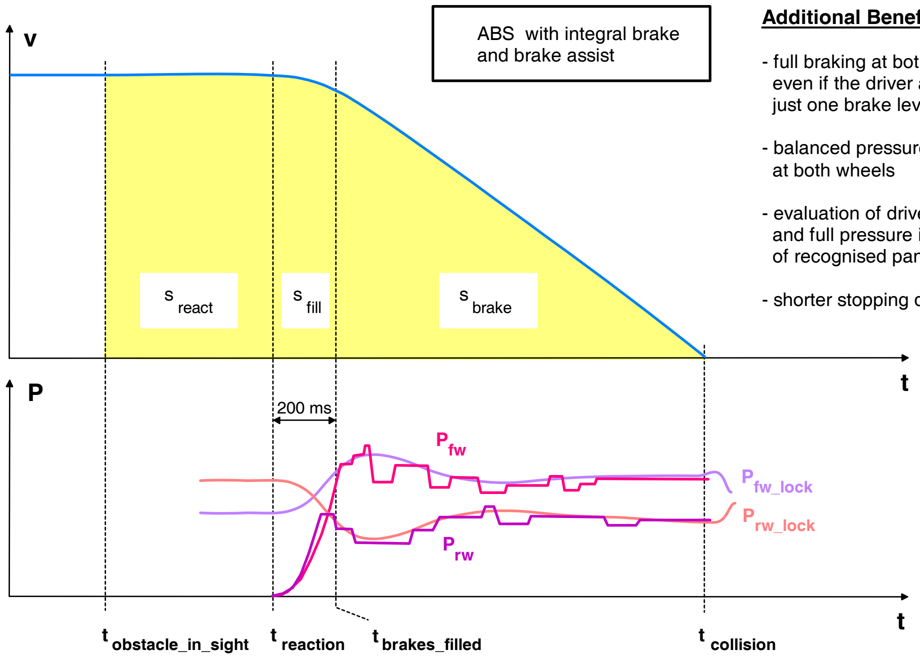
$t\_collision = t\_brakes\_filled$
$+ 2 * s\_brake / (v\_initial + v\_collision)$

→
$delta\_T\_c_{INT} = -0.2s$
$+ 2 * s\_brake_{INT} / (v\_initial + v\_collision_{INT})$
$- 2 * s\_brake / (v\_initial + v\_collision)$

In order to get a feeling for the effects of the integral brake and brake-assist control, the same example as above is looked at again.

v_initial = 26 m/s
s_brake = 26 m
v_collision = 19.4 m/s

→
$s\_brake_{INT} = 31.2$ m
$a\_brake_{INT} = 1g = 9.81 m/s^2$
$s\_brake\_needed_{INT} = 34.45$ m
$v\_collision_{INT} = 7.99$ m / s
$delta\_T\_c_{INT} = 0.485$ s



Additional Benefits:

- full braking at both wheels, even if the driver applies just one brake lever
- balanced pressure amounts at both wheels
- evaluation of driver brake pattern, and full pressure increase in case of recognised panic braking
- shorter stopping distances

Figure 6.
Time diagram of a panic-braking situation with ABS, brake-assist and integral brake

Even now the collision speed seems to be quite high with about 8 m/s, but we have to take into consideration that it is reduced by 11.4 m/s, what can really be life-saving for the PTW driver. Moreover, the crash, if it had happened at all, would have been delayed by a time interval of 0.485 s. This gives us an idea about the chances of the PTW driver to avoid the collision.
The additional benefits of this system are listed in fig. 6.

PTW braking with ABS control, integral brake, brake-assist and automatic pre-fill function

In the following step the advantages of an advanced driver-assistance system (ADAS) are described. This system is based on environmental sensors and an algorithm for danger calculation. In case of recognising a relevant obstacle, the system is able to pre-fill the brakes actively without any driver intervention (see fig. 7). This normally leads to a maximum deceleration of about 0.3g until the driver takes over and applies the brakes himself.
It is very difficult to make an assumption, when the system could have reacted in the studied accident cases and if the driver would have been aware of the danger a little sooner due to the automatic deceleration.
In order to be able to get a result and an idea of the possibilities at all, the following assumptions were made for each DEKRA case:

- 150 ms after the obstacle occurred, the system gets active and starts filling the brakes.
- It takes another 100 ms to pre-fill the brakes with an amount of pressure, which leads to a medium deceleration of 0.3g until the brakes are filled
- The reaction time of the driver is the same as described in the studied cases.
- With the help of ABS, integral brake and brake-assist, the driver is now able to perform a full brake application in just 120 ms, because the brakes are already pre-filled.

With these assumptions, the following simplified calculation can be done in a similar manner as above:

Available distance for full braking:

$$s\_brake_{ADAS} = s\_brake + (0.28s * v\_initial)$$

Due to the pre-filling and automatic deceleration of 0.3s the initial speed is now reduced, when the driver takes over:

$$v\_initial_{ADAS} = v\_initial – (t\_brakes\_filled – t\_obstacle\_in\_sight – 0.25s) * 0.3g$$

with

$$t\_brakes\_filled - t\_obstacle\_in\_sight = (s\_obstacle\_in\_sight – s\_brake) / v\_initial$$

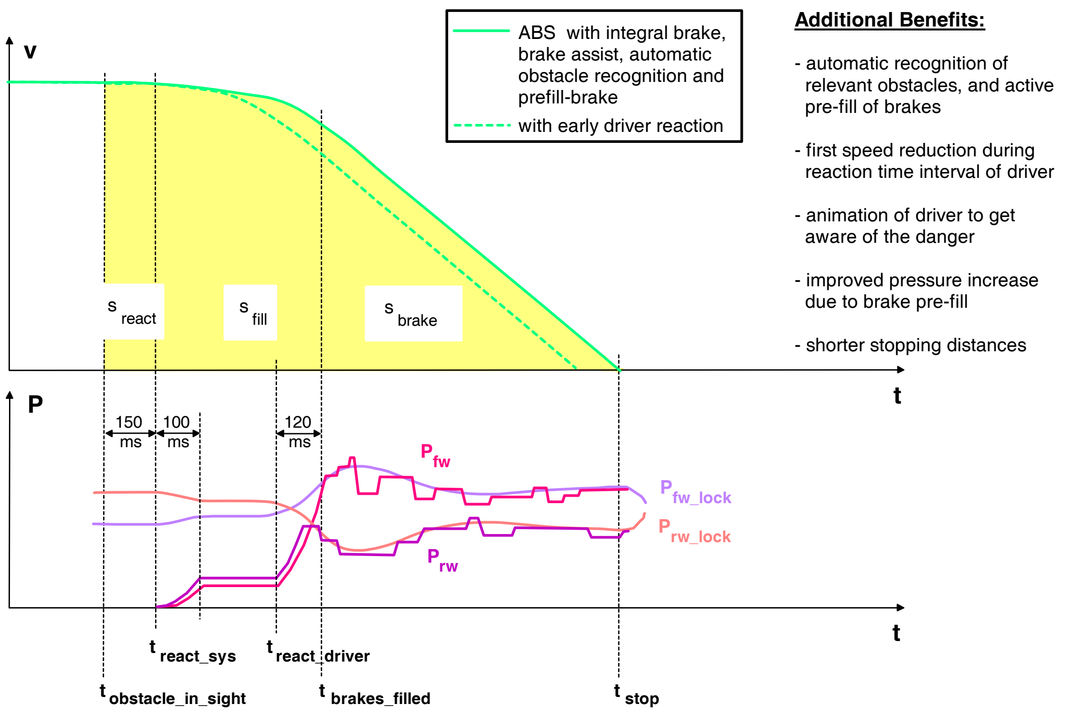


Figure 7. Time diagram of a panic-braking situation with ABS, integral brake and ADAS

The value for s_obstacle_in_sight, s_brake and v_initial are the original values from the database. The 0.28s result from the assumption that the brakes are now fully applied in 0.12s, that means 0.28s earlier than with the conventional braking.

Needed distance for full braking with the above assumed deceleration:

$s\_brake\_needed_{ADAS} = \frac{1}{2} * (v\_initial_{ADAS})^2 / a\_brake_{ADAS}$

If the needed distance $s\_brake\_needed_{ADAS}$ is lower than the available distance s_brake_{ADAS} no collision would have occurred. Otherwise the collision speed would have been

$v\_collision_{ADAS} = sqrt(2 * a\_brake_{ADAS} * (s\_brake\_needed_{ADAS} - s\_brake_{ADAS}))$

If a collision had occurred, the time step of the crash would have been delayed by $delta\_T\_c_{ADAS}$ compared to the situation without ABS:

$delta\_T\_c_{ADAS} = t\_collision_{ADAS} - t\_collision$

$t\_collision_{ADAS} = t\_brakes\_filled - 0.28s + 2 * s\_brake_{ADAS} / ((v\_initial_{ADAS} + v\_collision_{ADAS})$

$t\_collision = t\_brakes\_filled + 2 * s\_brake / (v\_initial + v\_collision)$

→
$delta\_T\_c_{ADAS} = - 0.28s + 2 * s\_brake_{ADAS} / (v\_initial_{ADAS} + v\_collision_{ADAS}) - 2 * s\_brake / (v\_initial + v\_collision)$

The effects of the system, consisting of ABS, integral brake, brake-assist control, and the driver assistance with automatic brake pre-fill, can be demonstrated with the same example as above:

v_initial = 26 m/s
s_brake = 26 m
v_collision = 19.4 m/s
s_obstacle_in_sight = 52 m

→

$v\_initial_{ADAS}$ = 23.8 m
s_brake_{ADAS} = 33.28 m

a_brake_{ADAS} = 1g = 9.81 m/s^2
$s\_brake\_needed_{ADAS}$ = 28.87 m
$v\_collision_{ADAS}$ = 0 m / s no collision, because $s\_brake\_needed_{ADAS}$ is lower than s_brake_{ADAS}

The additional benefits of this system are listed in fig. 7.
The dashed line is the vehicle speed in case of a very early driver reaction, which may occur in many cases as a result of the pre-braking done by the assistance system. The slight jerk caused by this pre-braking is felt as an indicator for an impending crash situation and can help the driver to come to a quicker decision and braking reaction.

RESULTS

Fig. 8 shows the vehicle velocities for all brake systems described above combined in one comparing time diagram.
When we take into consideration that the area below the respective velocity line is the stopping distance travelled through by the PTW during a dangerous braking manoeuvre, it is easy to imagine, what advantages can result from new electronic brake systems.

The overall result of the above estimation done for 51 DEKRA accident cases is shown in fig. 9 and fig. 10.
In fig. 9 we can see, how many of the 51 studied accidents could have been avoided or highly mitigated with the help of the respective brake system or braking behaviour of the driver.

The black frame bar marks the number of the 51 cases. The coloured bars represent the numbers of collisions, which would have been totally avoided due to the higher braking deceleration with the according brake-control system (first value on the bar). The hatched bars show the numbers of collisions, for which the collision speeds of the PTWs could have been reduced below 8m/s (second value on the bar). In these cases, the energy of the crashes would have been rather low, and moreover, due to the reduced speed and the gained reaction time before the crossing of the collision courses, we can assume, that the driver would really have had a chance to avoid the crash by steering.
In order to get a feeling of the overall effect of the collision speed reduction, fig. 10 may be looked at.
With the help of the described electronic brake control systems the medium collision speeds presented by the bar graph could be reduced considerably.

Even the system with the lowest expenditure, the 2-channel ABS, offers an impressive chance to mitigate the effects of impending crash situations. If the driver is fully aware of these facilities and

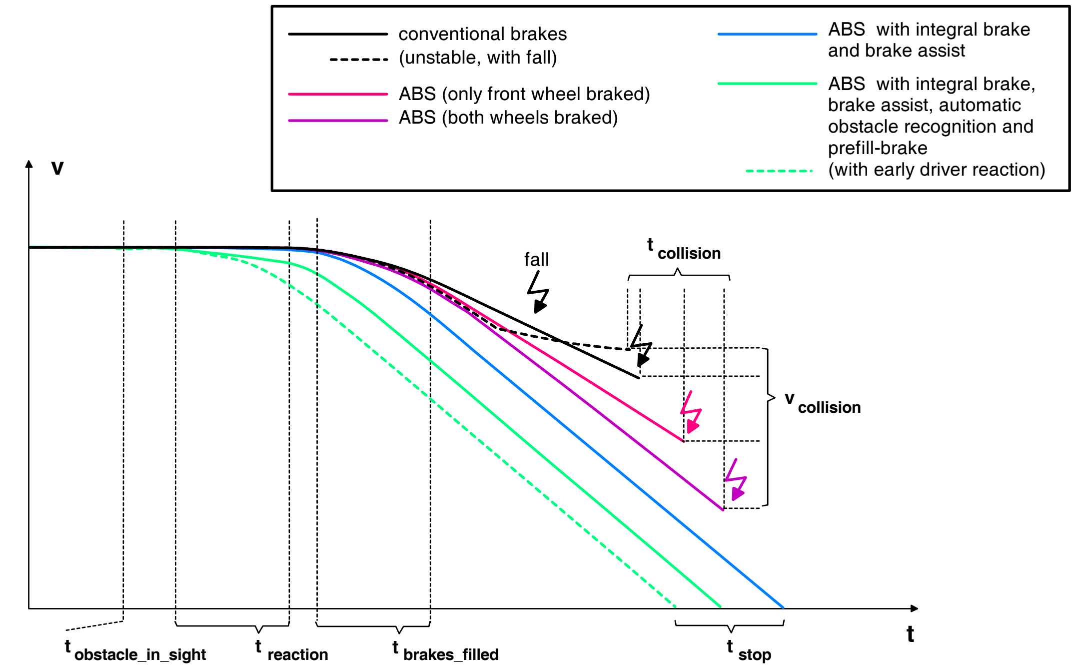


Figure 8. Time diagram of a panic-braking situation with different brake control systems

learns to rely on his anti-lock brakes, he will get used to hard and simultaneous braking with both brake levers. The potential of reducing collision speeds to about 50 or even 40% can already be life-saving and prevent the PTW driver from getting seriously injured, even if the impending crash is unavoidable.

As we know from the laws of physical science, the demolition effect caused by a collision is increased with the kinetic energy of the crash partners in a proportional manner, and the energy itself is increased with the square of the velocity. Therefore, reducing the collision speed to the half amount means reducing the demolition effect to

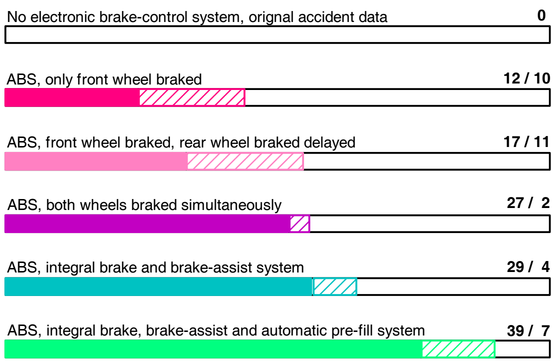


Figure 9. Numbers of accidents avoidable depending on different brake control systems

just a quarter of the actual amount.

This means for the 2 channel ABS handled properly by simultaneous braking of both channels, that the medium demolition effects could have been reduced below 20%.

But nevertheless, the most important advantage of reducing the speed of the PTWs is yielded by the fact that the manoeuvrability and steerability of a PTW are highly improved for low velocities. Moreover, the driver gains more time to make a steering decision, because the crossing of the collision courses is delayed due to the higher PTW deceleration.

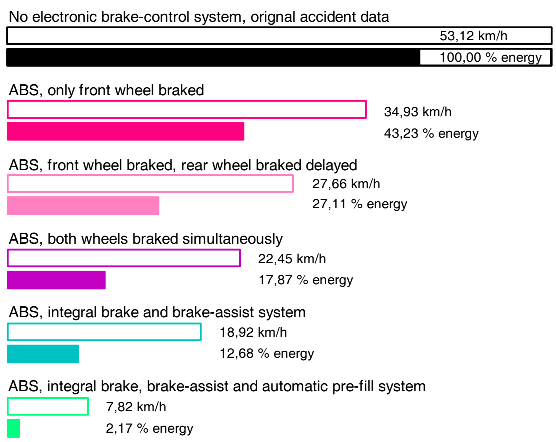


Figure 10. Medium collision speeds and percentile crash energy depending on different brake control systems

CONCLUSION

As we can see from the PTW deceleration data provided by the DEKRA database, most drivers do not use the maximum brake performance due to the fact, that they are aware of the danger of wheel overbraking. The concentration on two brake levers is certainly a big problem and seems likely to disable drivers concerning the manoeuvring decisions necessary to avoid collisions. The low medium deceleration values show us further that drivers need long time intervals to get the brakes filled and find operating points which are at least near the optimum.

The most important task of ABS is to exploit the maximum friction amounts between tires and road surface and nevertheless to provide the PTW with sufficient driving stability for the performed manoeuvre.

But the even more important effect of antilock brake control for motorcycles should be, that the system gives the driver confidence concerning braking stability even in case of hard brake application. As the above calculations show us unambiguously the best way of reducing speed in time is to have an early and hard brake activation. Saving just 100 or 200ms of brake-filling time means to reduce the whole stopping distance considerably. The driver must be sure that the brake control can be relied on, that there is no risk of wheel-locking, and he should learn to perform full-braking with ABS, simultaneously with both brake levers or at least with the front brake lever in case of a PTW equipped with integral-brake facilities.

Moreover, ADAS systems may be very much of help to make time-saving decisions automatically. Among the 51 studied DEKRA cases are only very few situations, which could not be managed by ADAS systems in a satisfying manner. These are situations which are characterized by so-called sudden cut-ins, meaning that an obstacle crosses the driving path of a PTW so abruptly, that a crash is unavoidable even in case of immediate full-braking.

At this point we see the limits of active safety systems, and that it is necessary to provide PTW drivers with passive safety as well.

In the EC-funded SIM-project, active and passive safety components for PTWs are investigated. In several test vehicles provided by Piaggio, the systems are connected via CAN-bus, so that important sensor and control-signal information can be interchanged. With the help of this networking, additional synergy effects are achieved.

REFERENCES

[1] Spiegel, Prof. Dr. B., „Über das Bremsen aus Sicht des Verhaltensforschers“, Eröffnungsvortrag des XX. Internationalen µ-Symposiums, Bad Neuenahr, Germany, 27. / 28. October 2000

DYNAMIC ANALYSIS OF SIDE-BY-SIDE UTILITY AND RECREATIONAL VEHICLES

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Paper Number 09-0260

ABSTRACT

Over the past several years, there has been seen an increasing popularity of side-by-side utility and recreational vehicles (also referred to as UTVs and ROVs), which resemble road-going passenger vehicles more so than typical ATVs due to bench/bucket seats, safety belts, steering wheels, etc. Some of these perceived safety advances over standard ATVs are reasons for their increased popularity. Therefore, it is important to begin using basic passenger car vehicle dynamics knowledge and testing techniques to enhance the safety of these vehicles by making them perform more like road-going vehicles in terms of both directional stability and rollover resistance.

Recent research by The Engineering Institute has resulted in a quantification of the performance aspects of a typical side-by-side using standard automobile tests such as SAE J266, ISO Avoidance Maneuvers, J-turns, and a slalom course. Simple vehicle modifications were also performed that dramatically improved the performance of the vehicle through the same maneuvers.

This paper will discuss the results of both the testing on the standard and modified vehicle. Data from the testing will be presented, and the vehicle modifications will be illustrated. Conclusions will be made detailing the effectiveness of using basic passenger car vehicle dynamics principles at drastically improving the safety of side-by-sides.

INTRODUCTION

Understeer, oversteer, static stability, and dynamic rollover resistance are basic principles of vehicle dynamics understood by engineers with a vehicle dynamics background.

Analysis of a vehicle's understeer or oversteer tendency is a good first approximation of a vehicle's directional controllability. In fact, SAE J266, the standard which describes the test methods for determining and quantifying the understeer or oversteer of a vehicle is entitled *Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks.* The scope of this document states that, "This SAE Recommended Practice establishes consistent test procedures for determination of steady-state directional control properties for passenger cars and light trucks with single axles." [1]

ISO 4138, *Passenger cars—Steady-state circular driving behavior—Open-loop test methods*, echoes this in its scope by saying, "This International Standard specifies open-loop test methods for determining the steady-state circular driving behaviour of passenger cars…, such behaviour being one of the factors comprising vehicle dynamics and road-holding properties." [2]

The static stability of a vehicle has long been recognized as a good first order approximation, albeit a conservative one, of a vehicle's rollover resistance. The National Highway Traffic Safety Administration (NHTSA) has described it as a "primary means" of determining the risk of rollover [3].

A vehicle's static stability is just that, static. Dynamic rollover resistance addresses the dynamic stability of a vehicle including suspension effects by testing the vehicle through various maneuvers including maneuvers which are considered limit-handling maneuvers.

VEHICLE TESTING

Typical Passenger Cars/Light Trucks

The majority of road-going vehicles exhibit linear-range and limit understeer when tested in accordance with SAE J266. These vehicles usually show a distinct upturn in the understeer gradient, measured by plotting the wheel angle in degrees versus the lateral acceleration corrected for the vehicle roll angle and taking the slope, as the vehicle nears the limits of tire adhesion. If the front tires of the vehicle reach their tractive limits prior to the rear, the vehicle understeers.

Figure 1 shows plots for a typical passenger vehicle which exhibited limit understeer during a clockwise and counterclockwise constant radius, slowly increasing speed test. Note that the slope is positive throughout the range of handling with a distinct increase in its positive slope up to the point that the tires have saturated, and the test driver is no longer able to keep the vehicle on path, the termination condition for the test.

For the tests plotted below, the vehicle was tested on an approximately 40 m radius circle.

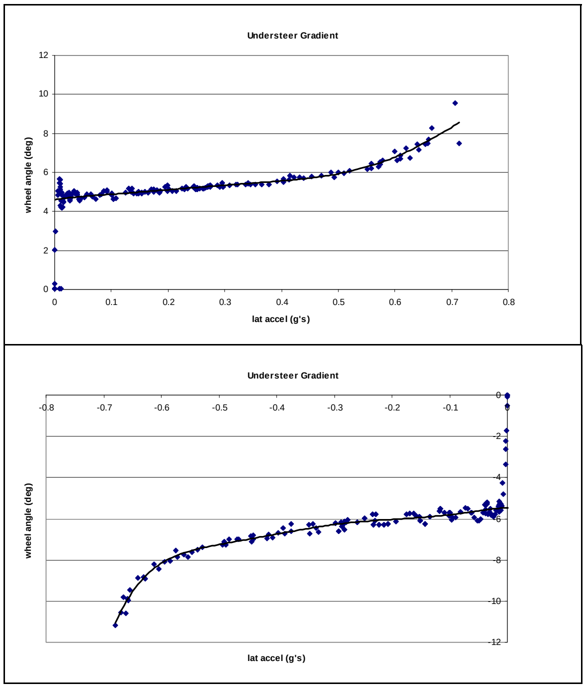


Figure 1. Understeer gradient plots for a typical passenger vehicle.

NHTSA has published data concerning the static stability in the form of the static stability factor.

$$SSF = \frac{1}{2}\frac{Trackwidth}{CG\ Height} \quad (1)$$

NHTSA's data shows a range from 0.95 for the 1992-2000 Mitsubishi Montero 4dr, 4X4 to nearly 1.8 for the previous generation Corvette.

With regards to dynamic rollover resistance, some road-going vehicles have been made to tip in limit-handling maneuvers at high lateral accelerations (0.8 g's +).

Side-by-Side Recreational Vehicle

<u>Static Analysis</u>-A side-by-side recreational vehicle was tested by The Engineering Institute.

Firstly, the vehicle was tested in order to determine its static stability factor, as a means of determining how it compared to the road-going vehicles previously tested by NHTSA. The center of gravity height of the vehicle was determined by locking the suspension and placing the vehicle on a tilt-table.

The protocol used was as follows:

- Document the vehicle "as received."
- Determine loading configurations to be tested.
- Place dummies and cargo (if applicable) in the vehicle to simulate the loading configurations.
- Measure shock/spring or strut/spring length at ride height for each loading configuration.
- Measure the track width for each.
- Fabricate adjustable suspension rods to fix the ride height at the measured values.
- Load the vehicle to the desired loading configuration and set the suspension rod to the corresponding length.
- Place the vehicle on the tilt table with the leading tires on the high friction surface and their edges against the wooden 11/16" high curb.
- Tether the trailing edge of the vehicle to the table so that the trailing tires can lift from the platform, but do not allow the vehicle to tip all the way over.
- Raise one side of the platform until both of the trailing tires lift from the platform.
- Document the angle at which this lift occurred.
- Perform at least two tests passenger side leading and two tests driver's side leading.
- If data is not consistent, perform additional tests.

The test vehicle was tested in four configurations. These were vehicle only, vehicle plus 73 kg water dummy in the driver's seat, vehicle plus 73 kg water dummies in both the driver's and passenger's seat, and vehicle plus two 73 kg water dummies and cargo placed in the bed up to GVWR.

The results of the static testing are summarized in Table 1.

Table 1.
SSF test results.

Configuration	Avg CG Height (mm)	Average SSF
Vehicle Only	622	0.88
Vehicle Plus 73 kg Driver	693	0.79
Vehicle Plus 73 kg Driver and Passenger	719	0.77
GVWR	790	0.71

Two things of note from the above table are that (1) the unloaded SSF of this vehicle is lower than that of any road-going vehicle as reported by NHTSA, and (2) the low curb weight of this type of vehicle results in passenger loading having a large effect on the static stability of the vehicle.

Dynamic Analysis-A vehicle whose static stability predicts tip-up at acceleration levels of less than 0.9 g's has a high risk of a rollover on a flat, level surface. In order to assess this, dynamic testing was carried out on the vehicle. The photograph below shows the vehicle prepared for dynamic testing.

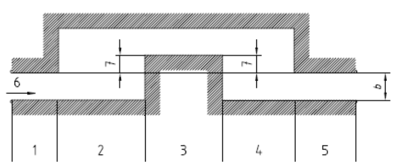
Figure 2. Test vehicle as prepared for testing (Yamaha Rhino 450).

To determine understeer/oversteer characteristics SAE J266: *Steady State Directional Control Test Procedures for Passenger Cars and Light Trucks* [1] constant radius, slowly increasing speed circle test was used as a test basis. These tests were conducted in both the clockwise and counterclockwise directions. *J266* recommends a minimum radius of approximately 30.5 m. However, due to the lower top-end speed of these vehicles, this radius was reduced to 15.25 m for this testing, resulting in a 30.5 m diameter circle. This diameter is in agreement with the Consumer Product Safety Commission's recommended use of a 30.5 m diameter circle test for ATV analysis to determine both the "maximum dynamic lateral acceleration in a turn" and the vehicle's understeer and oversteer characteristics in their *All Terrain Vehicles (ATVs) Project Status Report, February, 2008* [4].

Though the steady state circle test is a good indicator of the amount of understeer designed into the vehicle, it is not very representative of any real world dynamic driving maneuvers. Therefore, dynamic maneuvers were also performed to evaluate the transient dynamics of the vehicle. The purpose was to subject the vehicle to maneuvers to evaluate the non steady-state handling characteristics of the vehicle. The standard maneuvers chosen were avoidance maneuvers, step-steers, and slalom courses. A non-standard maneuver which was also evaluated was a U-turn from a stop or from a slow rolling speed.

The vehicle was driven at various speeds through an accident avoidance maneuver. The avoidance maneuver was patterned after the ISO International Standard 3888-2 *Passenger cars — Test track for a severe lane-change manoeuvre —Part 2: Obstacle avoidance* [5]. The width measurements for this course are based on vehicle width. Figure 3 shows the track and dimensions. As shown in the figure, the driver operates the vehicle through Section 1 in the direction marked by the number 6. As the driver enters Section 2, he/she steers left then right to enter the offset Section 3 (i.e. avoid an obstacle in the path of Section 1). At the end of Section 3 as the vehicle is entering Section 4, the driver steers right then left to enter Section 5.

ISO 3888-2:2002(E)



Key
1 Section 1
2 Section 2
3 Section 3
4 Section 4
5 Section 5
6 Driving direction
7 Lane offset

Figure 1 — Obstacle avoidance track with designation of sections

Table 1 — Obstacle avoidance track dimensions

Dimensions in metres

Section	Length	Lane offset	Width b
1	12	—	1,1 × vehicle width + 0,25
2	13,5	—	—
3	11	1	vehicle width + 1
4[a]	12,5	—	—
5	12	—	1,3 × vehicle width + 0,25, but not less than 3 m

[a] To ensure high lateral accelerations at the end of the track, section 4 is 1 m shorter than section 2.

Figure 3. ISO avoidance maneuver illustration and dimensions. [5]

The ISO standard calls for the vehicle throttle (gas pedal) to be released at the entrance speed at the timing strip. Due to the large amount of drag and engine braking with this vehicle, at the timing strip, the vehicle was shifted into neutral as the throttle was released. After the throttle release, the driver steers left then right to enter the offset lane. At the end of the offset lane, the driver steers right then left to reenter the last lane. The standard states: *The obstacle avoidance manoeuvre is a dynamic process which involves rapidly driving a vehicle from its initial lane to another lane parallel to the first, and returning to the initial lane, without exceeding lane boundaries. The objective is to have the vehicle reach a certain sequence of alternate high, lateral accelerations such that the vehicle's lateral dynamics can be evaluated.*

A second maneuver used was a step steer maneuver with various speeds. During this maneuver the driver reached the target speed and rapidly applied the predetermined steering angle and then held the steering and throttle constant. 180 degree and 270 degree target step steers were conducted at various speeds. The step steer test is patterned after ISO 7401, *Road vehicles — Lateral transient response test methods — Open-loop test methods* [6].

A third maneuver was based on the slalom maneuver used by Chrysler. Due to the relatively low top speed of this vehicle, the spacing between cones in the slalom was set to 15.25 m.

A non-standard maneuver used for vehicle evaluation was a U-turn accelerating from a stop and from low speeds. During this maneuver, the driver accelerated while turning the steering wheel sharply to complete a U-turn.

The testing was conducted on flat, level concrete for repeatability and comparison purposes as well as a grass surface.

<u>Circle Testing Analysis</u>-During the circle testing, the side-by-side exhibited both understeer and a transition to oversteer. This transition placed a high burden on the driver, as constant corrective steering in the form of a reduction in the steering angle was necessary to keep the vehicle on path. The vehicle would suddenly lose rear grip at which time the yaw rate would quickly increase (see Figure 4) and the driver would have to arrest this with counter-steer. This made the vehicle highly unpredictable. Test video shows the driver constantly sawing the steering wheel to remain on radius.

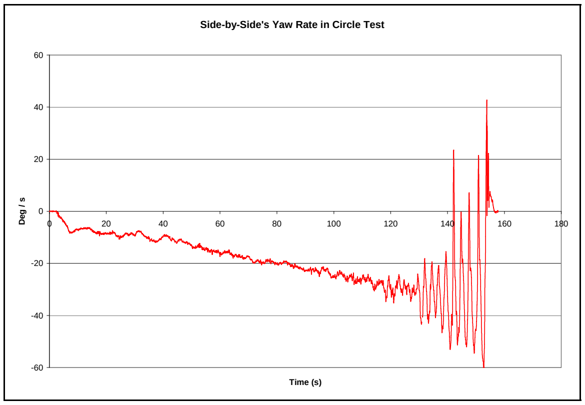


Figure 4. Yaw rates from circle test.

After the test data was processed, understeer plots were generated. These plots clearly show just how unpredictable and directionally unstable the vehicle is. The plots also indicate that the vehicle is beginning the transition to an oversteer vehicle at very low lateral accelerations of 0.25 g's, a value that is typically still considered the steady-state range of vehicle operation.

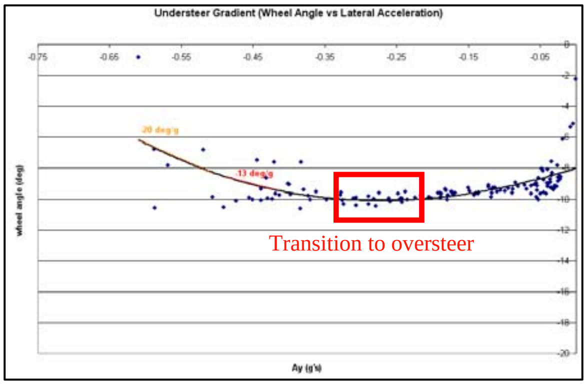


Figure 5. Understeer gradient plot showing transition to oversteer at 0.25 g's and terminal oversteer.

Not only did the vehicle exhibit directional instability in the circle testing, the vehicle even tipped onto the outriggers during the circle testing. As seen from the above plot, the maximum lateral acceleration attained in the testing was less than 0.65 g's.

<u>Obstacle Avoidance Testing Analysis</u>-The avoidance maneuver showed similar results to those seen in the circle testing. The vehicle exhibited a sudden loss of grip at the rear (indicated on the plots by the high yaw rates as shown in Figure 6 for example) and if this was not arrested, the vehicle tipped. The tips in the avoidance maneuver occurred at a similar lateral acceleration as in the circle test with a value of 0.67 g's.

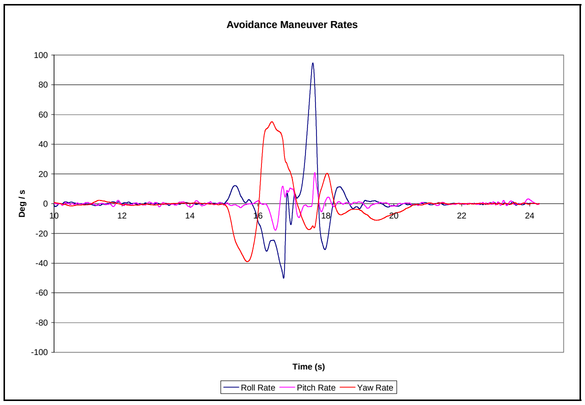


Figure 6. Plot of rates (yaw rate in red) from an avoidance maneuver that resulted in rollover.

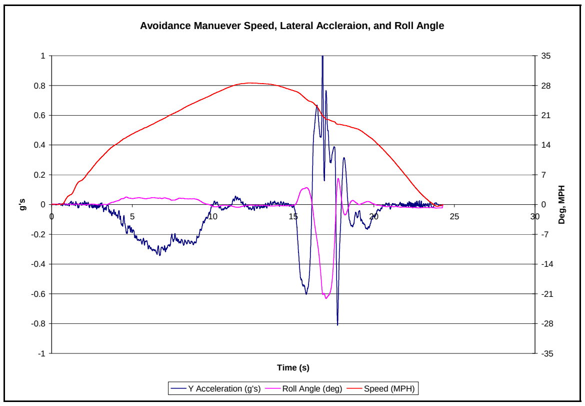


Figure 7. Avoidance maneuver plot showing speed, lateral acceleration, and roll angle.

<u>Step-Steer Testing Analysis</u>-The step-steers resulted in tip-ups at the lowest lateral accelerations of any of the tests. Tip-up occurred in 8 of the 18 step steer tests performed on the first day of testing with lateral accelerations as low as 0.55 g's, an extremely low lateral acceleration to cause tip-up.

Figure 8 shows this. Note that the speed at tip is around 14 mph (22.5 kph).

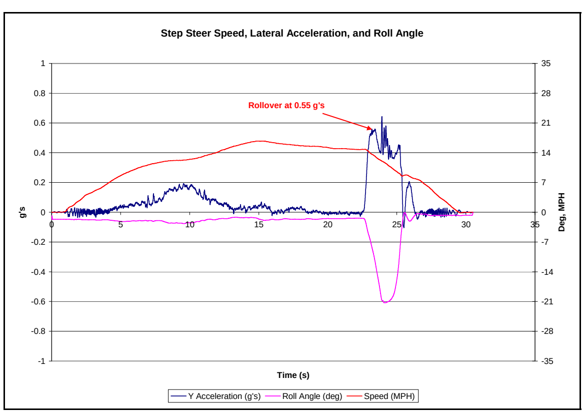


Figure 8. Step steer test data.

<u>Slalom Testing Analysis</u>-During the slalom test, the dynamics echoed those from the circle and avoidance maneuvers. The vehicle exhibited oversteer during the mauever, and could be made to drift around the cones. Tip occurred in these tests at 0.57 g's.

<u>U-Turn While Accelerating Testing Analysis</u>-During this type of test, the vehicle tipped onto the outriggers at a lower speed than in any other tests, approximately 19 kph (12 mph). Tip occurred consistently in the lateral acceleration range of 0.57 to 0.63 g's.

<u>General Analysis of Dynamic Testing</u>-The dynamic testing revealed a two-part instability with the vehicle. The vehicle consistently showed a loss of directional stability due to a loss of grip at the rear tires sometimes followed by a tip-up of the vehicle onto two wheels or completely onto the outriggers.

Figure 9. Frame capture from vehicle testing showing onset of loss of directional stability characterized by a lifting of the inside rear tire (the green is speed in mph).

As was felt by the test driver, and is easily seen during the maneuvers and in Figure 9, the loss of rear grip is instigated by a lifting of the inside rear wheel during a turning maneuver. This indicates that the rear of the vehicle is too stiff in relation to the front. The 2000 Edition of the SAE *Manual on Design and Manufacture of Torsion Bar Springs and Stabilizer Bars* [7] warns against a rear-only stabilizer bar. The manual states that, "Stabilizer bars are generally installed on both front and rear suspensions or in front suspension only. Use of a stabilizer bar on the rear suspension only can sometimes have an adverse effect on vehicle handling. Such installations should be tested under severe cornering conditions to ensure the desired handling characteristics."

The use of the anti-sway bar on the rear of the vehicle is mandated by the rear-drive. The rear drive of the test vehicle does not employ a differential, rather the axle shafts are splined and both shafts are driven at the same angular speed. This configuration would result in heavy tire scrub and understeer while cornering if not for the anti-sway bar being used to unweight and lift the inside tire. This lifting of the inside rear wheel is highly derogatory to the vehicle handling.

Appendix A is a summary table of the first set of the standard vehicle testing.

Vehicle Modifications-The vehicle was modified with a two-fold purpose. The goals were (1) to increase the directional stability and (2) to increase the rollover resistance. A secondary aim was to achieve these goals with as simple vehicle modifications as possible.

Simple vehicle dynamics principles were employed to accomplish these goals. In order to increase the directional stability, it was known that the roll stiffness balance needed to be altered to reduce that of the rear of the vehicle in relation to the front. To accomplish this, it was decided that the rear anti-sway bar must be removed. As discussed earlier, severe tire scrub and understeer would result if this was the only modification made. Therefore, a modification to the rear-drive had to be made as well. The test vehicle is a four-wheel-drive model which employs a front differential. The front differential was taken from another vehicle and mounted on the rear of the test vehicle.

In order to increase the rollover resistance, there were two basic options as evident from Equation 1. The center of gravity height could be lowered or the trackwidth could be widened. The second option was easy to perform as aluminum wheel spacers are currently on the market for this type of vehicle. In fact, the website from which the spacers were ordered advertised them as increasing the cornering stability. The spacers are approximately 5 cm wide. Two spacers were added at each corner giving a little over 20 cm increase of the front and rear trackwidth. The modifications are shown below.

Figure 10. Modifications to the test vehicle.

Modified Vehicle Dynamic Testing Analysis-The vehicle modifications drastically improved the vehicle stability. The vehicle was much more directionally stable and predictable. The rollover resistance was also greatly improved.

The modified vehicle performed dramatically better in the circle testing. The vehicle exhibited linear range understeer with the understeer increasing until the test was terminated with limit understeer in both directions. The vehicle did not tip onto the outriggers in either test.

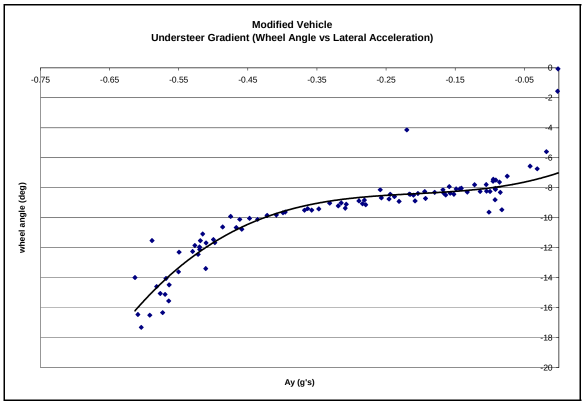


Figure 11. Circle test data plot for the modified vehicle.

The alternative design performed significantly better in the 15.25 m slalom testing. The vehicle had successful runs through the course with recorded lateral accelerations of 0.43, 0.64, and 0.83 g's with no tips onto the outriggers. During the slalom, the standard vehicle rolled over at 0.57 and 0.62 g's. The alternative design required 0.85 g's to rollover. The alternative design rolled over on the fourth steer after the roll momentum had built up throughout the maneuver. 0.85 g's is a 49% increase over 0.57 and is a 37% increase over 0.62 g's. Further tuning of the suspension system through spring rate modifications would likely eliminate rollover.

The alternative design did not roll over in any of the 180 degree left step steers even with lateral accelerations as high as 0.87 g's with a corresponding entrance speed of 51.5 kph. The standard design did rollover at 0.68 g's in the 180 degree left step steer. The alternative design did roll over onto the outriggers at 0.88 g's in the 270 degree left step steer with and entrance speed of 29 mph. The standard configuration rolled over at only 16 mph with a lateral acceleration of 0.68 g's. A 0.88 g rollover threshold equates to a 29% increase over 0.68 g's.

The alternative design did not roll at all in any of the four U-turn tests; whereas, the standard design rolled over in 11 out of 12 tests with speeds of approximately 19 kph at the time of rollover.

Appendix A shows a summary of the modified testing.

CONCLUSIONS

The following conclusions were made based on the dynamic testing of the side-by-side vehicle.

Testing revealed the standard configuration side-by-side is directionally unstable characterized by a transition to severe oversteer at lateral accelerations as low as 0.25 to 0.3 g's.

A variety of test maneuvers on concrete and on grass demonstrated that this vehicle will roll over from driver steering inputs at low lateral acceleration levels. Testing demonstrated rollovers at lateral accelerations as low as 0.55 g's. This rollover threshold is very low and can easily be exceeded even during proper use of the vehicle.

Testing of the alternative design showed that simple design changes greatly increased the directional stability. The alternative design showed a drastic improvement in the rollover threshold of this vehicle as well with lateral accelerations as high as 0.87 g's on concrete not resulting in rollover.

REFERENCES

1. SAE J266, *Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks*, Society of Automotive Engineers, 1996.
2. ISO 4138:2004, *Passenger cars—Steady-state circular driving behavior—Open-loop test methods*, Third edition 2004-09-15, International Organization for Standardization, 2004.
3. Walz, M.C., DOT HS 809 868 *Trends in the Static Stability Factor of Passenger Cars, Light Trucks, and Vans*, NHTSA, 2005.
4. Consumer Product Safety Commission, *All-Terrain Vehicles (ATVs) Project Status Report*, February, 2008.
5. ISO 3888-2:2002, *Passenger cars—Test track for a severe lane-change manoeuvre—Part 2: Obstacle avoidance*, First edition 2002-11-15, International Organization for Standardization, 2002.
6. ISO 7401:2003, *Road vehicles—Lateral transient response test methods—Open-loop test methods*, Second edition 2003-02-15, International Organization for Standardization, 2003.
7. *SAE Manual on Design and Manufacture of Torsion Bar Springs and Stabilizer Bars, 2000 Edition, HS-796*, Society of Automotive Engineers, 2000 revision.

Appendix A: Summary Table of Standard and Modified Vehicle Testing

Table 2.
Summary of standard configuration testing.

Test #	Test Type	Target Speed (mph)	Actual Speed (mph)	Tip?	Approx Lat Accel at Tip (g's)	Max Lat Accel for Manuever with No Tip (g's)	Notes
1	Circle, CCW	N/A	N/A	Y	0.74		
2	Circle, CW	N/A	N/A	N			Data acquisition error
3	50 ft. Slalom	15		N			Data acquisition error
4	50 ft. Slalom	20		N			Data acquisition error
5	50 ft. Slalom	25					System power off, run aborted
6	50 ft. Slalom	25	25	N		0.7	
7	50 ft. Slalom	25	25.5	Y	0.57		
8	ISO Avoidance	20	20	N		0.31	
9	ISO Avoidance	25	25	N		0.54	
10	ISO Avoidance	30	29	N		0.48	
11	ISO Avoidance	30	30	Y	0.67		
12	ISO Avoidance	28	27	Y	0.67		
13	ISO Avoidance	26	26			0.61	
14	180 deg Left Step Steer	15	13.5	N		0.49	Steer stop moved, exceeded 180 deg
15	180 deg Left Step Steer	15	14.5	N		0.45	
16	180 deg Left Step Steer	18	18.5	N		0.67	
17	180 deg Left Step Steer	20	20.5	Y	0.68		
18	180 deg Left Step Steer	19	19	N		0.67	
19	180 deg Left Step Steer	20	20.5	Y	0.68		
20	270 deg Left Step Steer	15	16	Y	0.68		
21	270 deg Left Step Steer	15	15	N		0.66	
22	270 deg Left Step Steer	14	14	N		0.66	On-board camera failed during test
23	270 deg Left Step Steer	17					On-board camera failed, run aborted
24	270 deg Left Step Steer	17	16.5	Y	0.66		
25	180 deg Right Step Steer	15	14	N		0.47	
26	180 deg Right Step Steer	17	16.5	N		0.56	
27	180 deg Right Step Steer	18	18	Y	0.58		
28	180 deg Right Step Steer	18	18	Y	0.57		
29	270 deg Right Step Steer	15	15	Y	0.55		
30	270 deg Right Step Steer	14	14	Y	0.56		
31	270 deg Right Step Steer	12	12	N		0.52	
32	U-Turn	N/A	N/A	Y	0.6		Steer sensor out of range
33	U-Turn	N/A	N/A	Y	0.61		Steer sensor out of range
34	U-Turn	N/A	N/A	Y	0.6		
35	U-Turn	N/A	N/A	Y	0.6		Steer sensor out of range
36	U-Turn	N/A	N/A	N		0.6	Steer sensor out of range
37	U-Turn	N/A	N/A	Y	0.57		
38	U-Turn	N/A	N/A	Y	0.63		
39	U-Turn	N/A	N/A	Y	0.59		
40	U-Turn	N/A	N/A	Y	0.6		Steer sensor out of range

Table 3.
Summary of modified configuration testing.

Test #	Test Type	Target Speed (mph)	Actual Speed (mph)	Tip?	Approx Lat Accel at Tip (g's)	Max Lat Accel for Manuever with No Tip (g's)	Notes
1	Circle, CCW	N/A	N/A	N		0.66	
2	Cicle, CW	N/A	N/A	N		0.63	
3	50 ft. Slalom	20	19	N		0.43	
4	50 ft. Slalom	25	26	N		0.64	
5	50 ft. Slalom	30	30	N		0.83	
6	50 ft. Slalom	30	32	Y	0.85		
7	180 deg Left Step Steer	20	21	N		0.7	
8	180 deg Left Step Steer	25	26	N		0.81	
9	180 deg Left Step Steer	30	31	N		0.87	
10	270 deg Left Step Steer	20	20	N		0.79	
11	270 deg Left Step Steer	25	25	N		0.85	
12	270 deg Left Step Steer	30	29	Y	0.88		
13	U-Turn	N/A	N/A	N		0.61	Steer sensor out of range
14	U-Turn	N/A	N/A	N		0.58	Steer sensor out of range
15	U-Turn	N/A	N/A	N		0.62	
16	U-Turn	N/A	N/A	N		0.62	Steer sensor out of range