JAPAN'S APPROACH FOR CAR TO TRUCK COMPATIBILITY IN HEAD-ON COLLISIONS

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ABSTRACT

This paper presents Japan's approach for car-to-truck compatibility in head-on collisions. Front Underrun Protection Devices (FUPDs) regulated by ECE-R93 are effective in preventing car underrun in head-on collisions with trucks. The Japan Automobile Research Institute (JARI) has studied accident analyses and crash tests involving FUPDs at the request of MLIT and the Japanese Automotive Manufacturers Association (JAMA). It is predicted that passenger car driver fatalities can be decreased by about 45% (36 people/year) by equipping heavy trucks with FUPDs.

In 2002, meetings to formulate the FUPD regulation were initiated, with members of the government (MLIT), industries (JAMA, JABIA), and institutes (JARI). One agenda item for the meeting was whether to admit cement-mixers and tipper trucks as an application exclusions. The off-road driving performance of cement-mixers and tipper trucks would decrease if they were equipped with FUPDs provided under ECE-R93. However, it is necessary to equip tipper trucks with FUPDs since the trucks are often driven on urban roads.

As a result of these discussions, we have eased the FUPD height for tipper trucks from 400 to 450mm, the height at which the height at which minimum off-road driving performance is united with a decrease in aggressiveness. Even with an FUPD height of 450mm, car driver fatalities can be reduced by 28%. The regulations for FUPDs was introduced into Japan in January, 2007.

INTRODUCTION

In head-on collisions of bonnet-type cars (sedans, wagons, hatchbacks, etc., hereafter referred to simply as cars) and heavy trucks, the car often underruns the front of the truck., and the car crew received the serious or fatal injuries (Figure 1) [1]. The crash safety performance of the car depends on the way its structural parts interact with the structural parts of the truck (Figure 2).

FUPD equipment that prevents the car from underrunning the truck is obligatory in Europe. The required strength and ground clearance of FUPDs are specified in the relevant regulations (ECE-R93)[2].

The top height of the front structural parts (Longitudinal Member: LM) of nearly all cars are distributed from 400mm to 600mm (Figure 3). Therefore, the ground clearance of FUPDs complying with ECE-R93 (400mm) is thought to be suitable for catching the LM. However, decreased off-road driving performances in tipper trucks equipped with FUPDs has become a problem.

We had been studying the introduction of FUPDs into Japan since 1992 (Figure 4). Meetings to formulate FUPD regulations were initiated in 2002, with members of MLIT, JAMA, JABIA, and JARI in attendance. This report describes the results of this research in Japan.

Figure 1. Example of car-to-truck accident (Reference cited [3]).

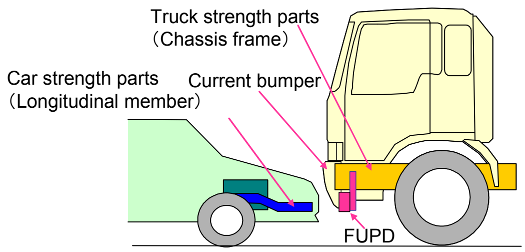


Figure 2. Relative height of front strength parts.

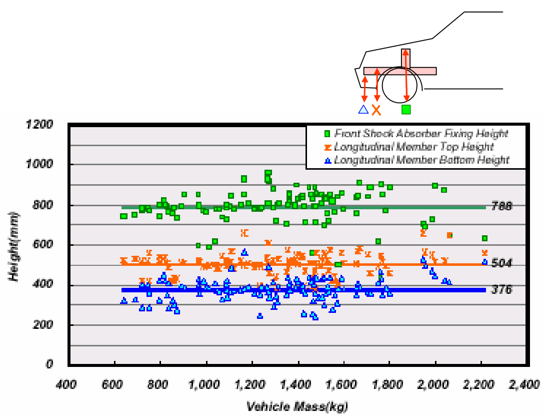


Figure 3. Ground clearance of passenger-car parts (New car registration from 1998; reference cited [4]).

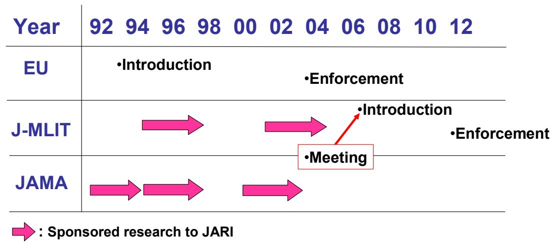


Figure 4. Research for the introducing of FUPD.

CAR-TO-TRUCK ACCIDENTS IN JAPAN

Accident Statistics in Japan

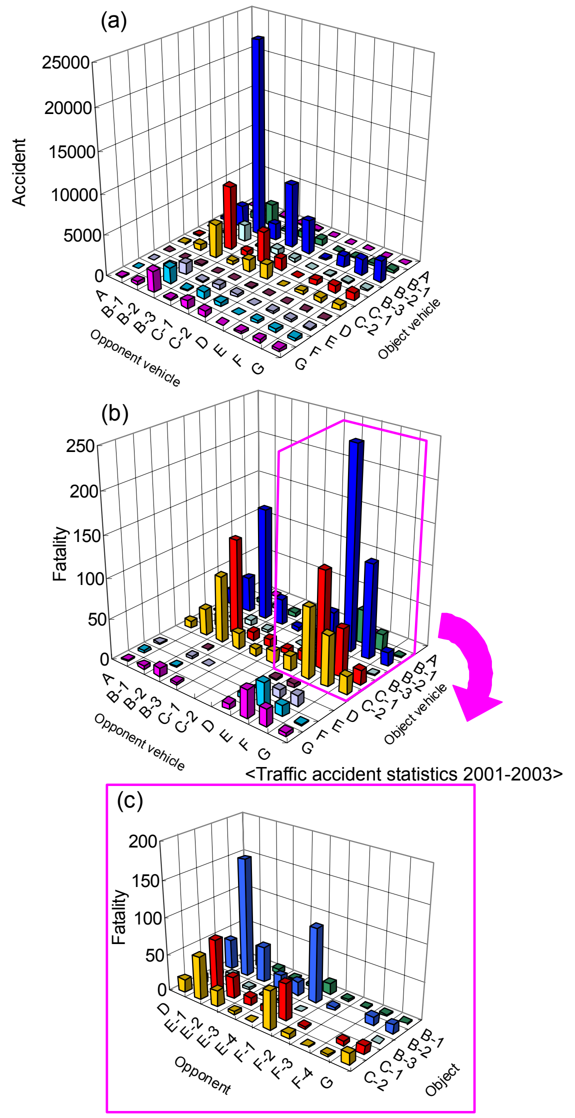
Collisions between cars and heavy trucks represent a serious problem in Japan, where trucks and cars drive together on nearly all roads. Figure 5 displays the vehicle correlations in head-on collision accidents. Figure 5 (a) indicates the number of accidents, and figure 5 (b) indicates the vehicle-driver fatalities. The right side (x-axis) of figure 5 (b) indicates the vehicle type driven in the cases with fatalities, with the left side (y-axis) indicating the opponent vehicle.

There is an overwhelming number of car-to-car accidents.

With respect to driver fatalities, there are many fatal accidents where the opponent vehicles are heavy trucks. The most frequent accident type occurs when car drivers collide with heavy trucks. The next highest frequency is represented by car-to-car accidents, "accidents of mini-car (bonnet type) vs. heavy truck ", "accidents of mini-car vs. sedan," and "accidents of car vs. midterm truck".

Figure 5 (c) shows the classification of vehicles (1-box. car, mini-car, etc.) vs. truck accidents, subdivided by truck type. There are many cargo and van types of heavy trucks, along with many cement-mixer and tipper types of heavy trucks. It is dangerous to disregard safety measures required for cement-mixers and tipper trucks, since they are involved in these types of accidents comparatively frequently.

Figure 6 shows the fatality rate (fatal injuries / all injuries) for the driver in five serious accident types according to seatbelt use. The fatality rate for mini-cars in accidents with heavy truck is the highest of all vehicle types. In collisions with heavy trucks, the fatality rate of drivers with seatbelts is one quarter of the rate of non-belted drivers. The car seatbelt works effectively in collisions with heavy trucks. But, the fatality rate of car drivers with seatbelts when colliding with heavy trucks is higher than the rate for non-belted drivers in car-to-car accidents. It is necessary to consider safety measures for the car crew in head-on collisions between cars and heavy trucks.



A :Bus
B-1: Cab-over car
B-2: Car (bonnet)
B-3: Car (SUV)
C-1: Mini car (bonnet)
C-2: Cab-over mini-car
D : Semi-truck
E Heavy truck (8t ≦GVW)
E-1: Cargo & van truck (8t ≦GVW)
E-2: C-mixer & tipper truck (8t ≦GVW)
E-3: Tank truck (8t ≦GVW)
E-4: Insulated truck (8t≦GVW)
F : Midterm truck (3.5t ≦GVW< 8t)
F-1: Cargo & van truck (3.5t≦GVW<8t)
F-2: C-mixer & tipper truck(3.5t≦GVW<8t)
F-3: Tank truck (3.5t ≦GVW< 8t)
F-4: Insulated truck (3.5t ≦GVW< 8t)
G : Small truck & Van (3.5t ≦GVW)

Figure 5. Vehicle correlations in head-on accidents.

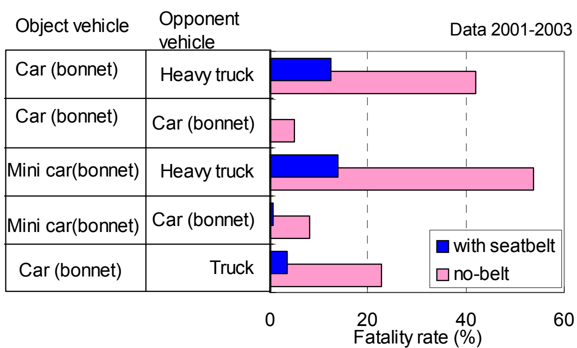


Figure 6. Fatality rate of the driver in five serious accidents according to seatbelt usage.

Analysis of In-depth Data

Head-on car-truck collisions were investigated in detail by using in-depth data from the Institute for Traffic Accident Research and Data Analysis (ITARDA). The trucks in the in-depth data were classified according to gross vehicle weight (GVW) as follows.

Heavy truck：semi-truck and 12t≦GVW

Middle truck：7.5t≦GVW＜12t

Light truck：3.5t≦GVW＜7.5t

Figure 7 depicts the deformation modes of the cars in head-on car-truck collisions. In this analysis, the deformation modes were classified into the following three types.

Type A: Only the upper part of the bonnet was crushed, and the LM of car has not collapsed directly. This mode may be caused by underrun.

Type B: The bonnet was evenly crushed for its upper and lower width, and the LM has collapsed. This mode cannot be caused by underrun.

Type C: The deformation could not be judged by underrun because the overlap was too narrow.

About 70% of collisions with heavy trucks involved type A deformation, with negligible amounts of type B. For middle trucks, about 55% of the deformations were of type A. Less than 10% of crashes caused type A deformation in light trucks. Type C deformation was caused at a rate of about 25% for each truck type.

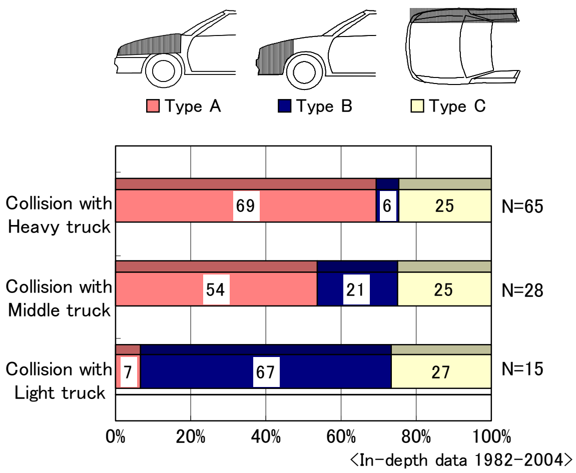


Figure 7. Deformation modes of bonnet cars [3].

Within type A or type C, the relation between the car overlap rate and the collapsing rate is illustrated in Figure. 8. Only heavy and medium trucks were considered, and only collisions with seat-belted car drivers were considered. Areas in the figure where death or injury occurred are indicated. The collapsing rate refers to Cs/Lo ("Crush length of the driver front " / "Bonnet length"), defined as shown to the right in the figure.

With overlaps greater than 30%, all deaths occurred at collapsing rates over 100%. Therefore, the main factor in these deaths is assumed to be a collapsing rate that exceeded 100%.

We investigated the equivalent barrier speed (EBS) in head-on car-truck collisions. EBS refers to the barrier collision speed at which a car deformation equal to that in the accident would occur, based on the results of past protruded-barrier collision tests.

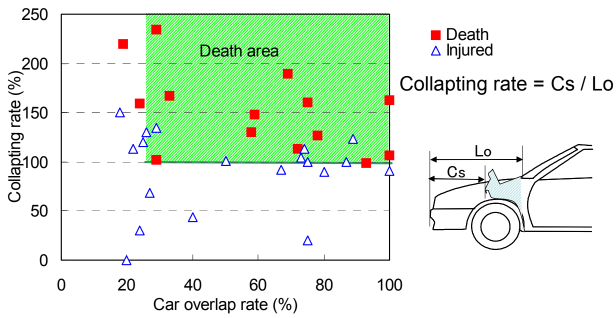


Figure 8. Relation between the car overlap rate and the collapsing rate (driver wearing seat-belt)[3].

Figure 9 illustrates the relation between the car overlap rate and the EBS of the car. Due to the limited number of data points, we included data from "non-belted drivers who died with collapsing rates over 100%" in addition to data points from "fatalities to seat-belted drivers". The trend did not change over the investigation year in although the data in figure 9 have been separated into 1982-1995 and 2000-2002 time periods.

The death line for the driver reveals a tendency for the EBS to rise with the overlap rate. The average EBS at a 50% overlap rate was about 65km/h. Most of the data points were in a range up to 20km/h faster than the death line. If the collapsing rate corresponding an EBS of to 20 km/h could be decreased, car crew fatalities would be significantly reduced.

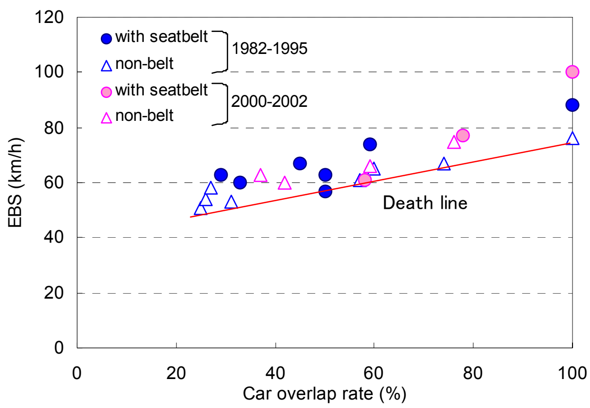


Figure 9. Relation between the car overlap rate and EBS [5].

CRASH TEST

Test Conditions

To check the effectiveness of equipping trucks with FUPDs, head-on car-truck collision tests were conducted (Figure 10). Trucks with and without FUPDs were used in these tests. The same car type and collision speeds were used in each test.

The crash matrix of the tests executed (total 24) is presented in Table 1. The test conditions were as follows.

- The test cars were collided with stationary trucks with the brake applied.
- Car speed at impact was 65 km/h (some tests were also performed at 50 km/h).
- Car overlap rates were 30%, 50%, and 100%.
- Two types of small sedans were investigated, along with a large sedan and a mini-car.
- A Hybrid-II dummy was installed in the driver's seat of the car, with a seatbelt. The injury criteria of the dummy were measured for reference. Only the mini-car was equipped with a driver airbag.
- The trucks used were mainly heavy trucks.
- The trucks were equipped with ringed-up FUPDs, corresponding to the strength specified in ECE-R93 for a height of 400mm. In these cases, existing resin bumpers were detached.

Figure 10. Example of a crash test [6]
(Heavy truck vs. small sedan, 100% lap).

Table 1.
Crash test forms

Passenger car \ Truck	lap	Heavy truck (GVW = 20t) without	Heavy truck (GVW = 20t) with FUPD	Middle truck (GVW = 8t) without	Middle truck (GVW = 8t) with FUPD	Ligth truck (GVW = 5t) without
mini car	50%		X	XX	XX	
	100%			X	X	
small sedan 1	50%	X	X	X	X	
	100%	X	X			
small sedan 2	30%	X	X			
	50%	XX	XX			X
	100%	X	X			
large-sedan	50%	X	X			

X: examined

Test Results

Figure 11 illustrates the deformation of a small sedan in 100% overlap collision with a heavy truck. In the collision without FUPD, car crushing reached the windshield. In contrast, the car collapsed only up to the front tire in the collision with the FUPD equipped.

Figure 12 illustrates the deformation of a small sedan in 50% collision with a heavy truck. The upper part was crushed to the A-pillar in the collision without FUPD, though the LM did not collapsed. The collapsing did not reach the A pillar in the collision with FUPD.

Figure 11. Deformation of the small sedan in 100% collision with the heavy truck.

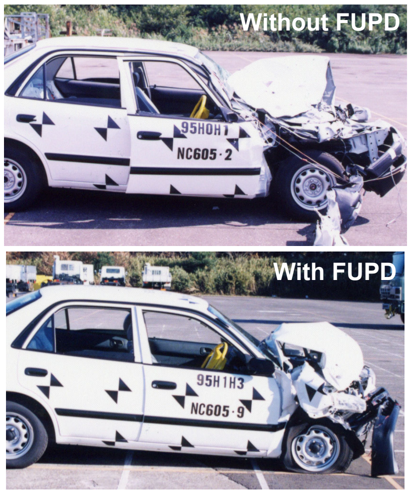


Figure 12. Deformation of the small sedan in 50% collision with the heavy truck.

Table 2 presents the results of classifying the car deformation modes according to the crash test configuration. Type A deformation was dominant in collisions with heavy trucks without FUPDs. Both type A and type B modes were present in collisions with middle trucks without FUPDs.
In collisions with FUPDs equipped, primarily type B was seen in most cars. It is thought that the dominant car deformation mode was changed from type A to type B by equipping the trucks with FUPDs. It can also be said that FUPDs prevented car from running under the trucks since type B deformation is not associated with underrun.

Table 2.
Car deformation modes

Passenger car	lap	Heavy truck (GVW = 20t) without	Heavy truck (GVW = 20t) with FUPD	Middle truck (GVW = 8t) without	Middle truck (GVW = 8t) with FUPD	Ligth truck (GVW = 5t) without
mini car	50%		B	A	B	
	100%			A	B	
small sedan 1	50%	A	B	B	B	
	100%	A	B			
small sedan 2	30%	A	C			
	50%	A	B			B
	100%	A	B			
large-sedan	50%	A	A			

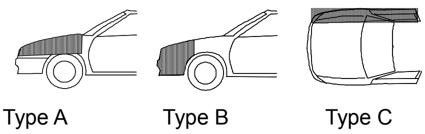


Figure 13 depicts the collapsing rate of crash configurations involving heavy trucks. The collapsing rate exceeded 100% in many cases without FUPD, but was reduced below 100% by equipping the truck with an FUPD. For mini-car collisions, the dummy injury criteria satisfied safety levels even though the collapsing rate exceeded 100% with FUPD equipped because the bonnet length is short. The collapsing rates presented are the results of crash tests executed at 65km/h. Other tests demonstrated that the collapsing rates change relatively with collision speed.

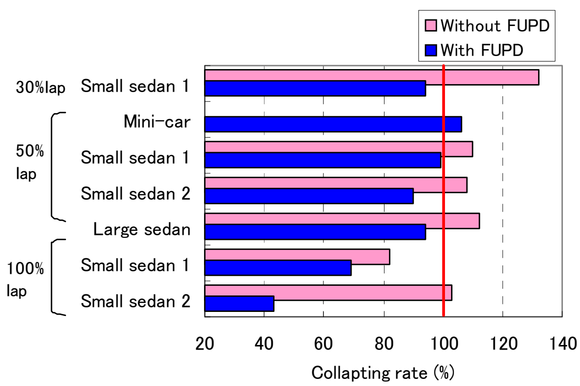


Figure 13. Collapsing rate due to collisions with heavy trucks.

Figurer 14 plots the relationship between the collapsing rate and specific dummy injury criteria (HIC, Femur force) for the driver. Each injury criterion tended to rise with increasing collapsing rate. There were some cases where the injury criterion exceeded the safety level that occurred with a collapsing rate greater than 100%.
There were other cases in which the HIC did not satisfy the safety levels. It is believed that the HIC exceeded the safety level due to a secondary impact of the dummy, since the survival space in the car was suitably retained. Also, these cars were not equipped with airbags. Equipping the cars with airbags is expected to lower HIC values.

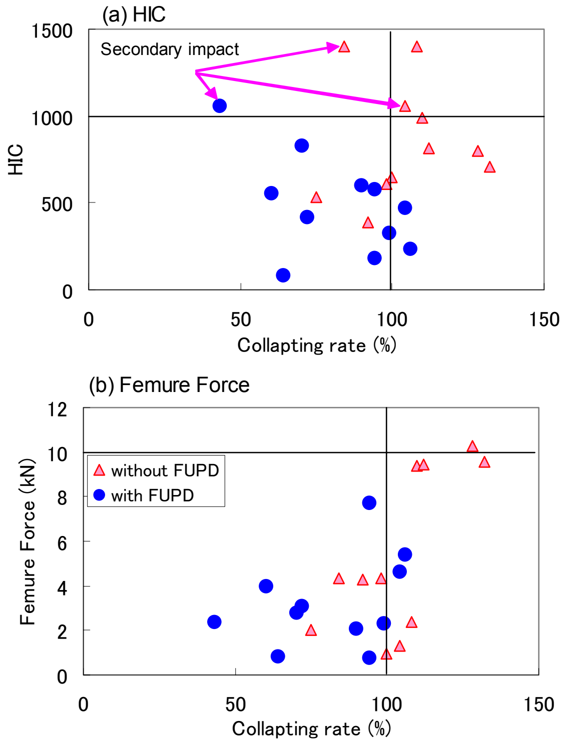


Figure 14. Relation between the collapsing rate and injury criteria

FORECAST OF FUPD EFFECT

Based on the fitting of FUPDs to current trucks, reductions in driver fatality rates were forecast for the following conditions.

- The targeted accident form of head-on collisions involving a car and a heavy truck (middle truck).
- The car driver wears a seatbelt.
- The fatality level is based on a collapsing rate that exceeds 100%.
- All trucks are assumed to be equipped with FUPDs according to ECE-R93.
- The FUPD effect is calculated by the following. The number of fatality-reductions/year multiplies "FUPD effect" and "period average of the car driver fatality".

FUPD effect = [Probability of underride] × [Contribution rate of FUPD]

"Probability of underrun" and "contribution rate of FUPD" were forecast by using the following two methods.

Forecast by In-depth Data

In this forecast, the effect of FUPDs in car vs. heavy truck accidents was forecast. The probability of underrun was derived from Figure. 7, which predicts a 69% probability of underrun with type A deformation present.

A contribution rate estimate was obtained by combining the crash test results with in-depth data. Figure. 14 plots the relation between the EBS and the collapsing rate. This graph plots both the in-depth data and the test results.

Looking at the results for 50%-74% lap, we see that the test results for trucks not equipped with FUPDs and the in-depth data lies in the same area. When the regression line for the in-depth data (without FUPD) is plotted, the collapsing rate is seen to reach 100% at 52km/h. The EBS of the results with FUPD is 25% higher than that of the results without FUPD, although the regression lines of the two cases are parallel.

The test results without FUPDs and the in-depth data are also in the same range for 25-49 lap and 75-100% lap. Therefore, the regression line for the results with FUPD was also assumed to be parallel to the results without FUPD. The EBS value at the point where the collapse rate reached 100% was obtained from each regression line.

Figure.15 portrays the relationship between the overlap rate and EBS values at 100% collapse. This relationship can be divided into three areas (A, B, and C).

Area A: In this area, the car driver dies even if the truck is equipped with FUPD.

Area B: In this area, the car driver lives if the truck is equipped with FUPD.

Area C: In this area, the car driver lives do to wearing a seatbelt, regardless of FUPD installation.

Therefore, fatalities that would be present in accidents in area B might be reduced by equipping the involved truck with an FUPD.

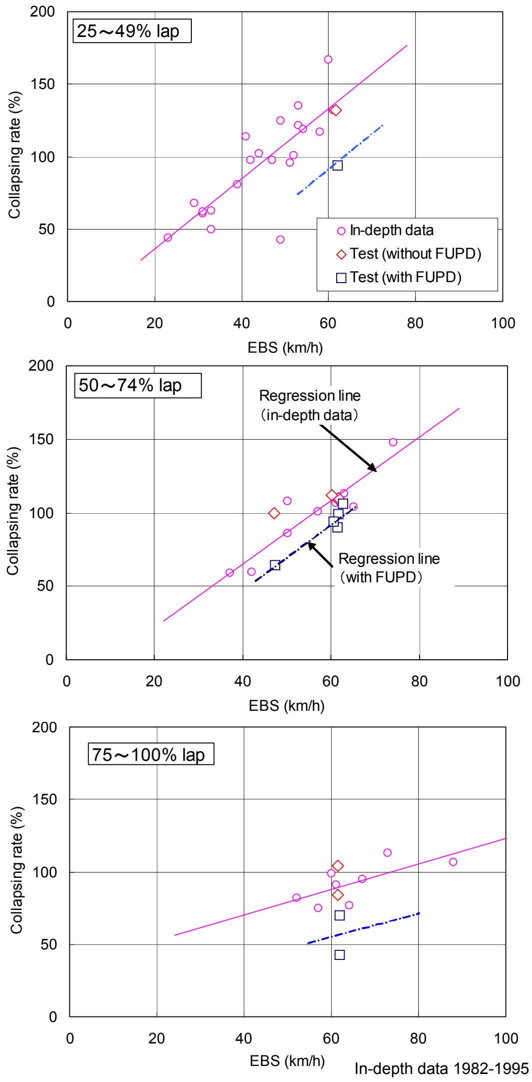


Figure 15. Relation between EBS and collapsing rate.

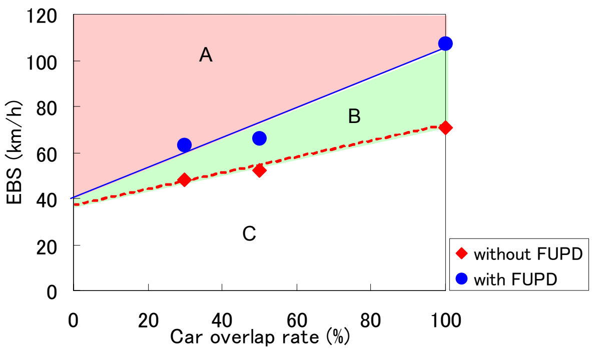


Figure 16. Relation between overlap rate and EBS when the collapsing rate reaches 100%.

Figure 17 presents the results of superimposing these areas onto Figure. 8. Here, 4 (of 18) people are distributed in area A and 14 people are distributed in area B. It is thought that 14/18 (78%) could be saved by equipping trucks with FUPDs. The contribution by FUPDs in this case is presumed to be 78%.
The forecast using in-depth data proceeds as follows.

FUPD effect = 69(%) * 78 (%)= 54 (%)

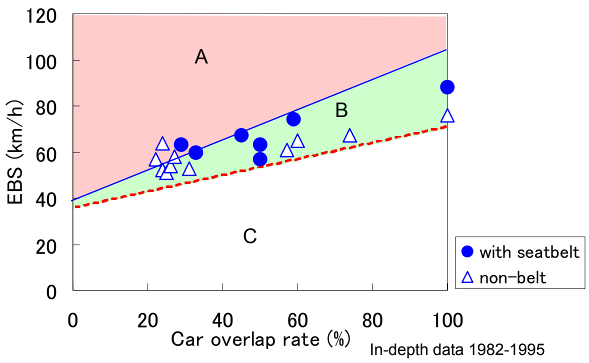


Figure 17. Contribution rate of FUPD.

Forecast by Macro Data
The forecast by macro data predicts the effect of FUPDs in accidents involving heavy and meddle trucks.
The car deformation modes were estimated from the LM of the new car registrations from 1998 and the chassis frame height of trucks. The modes were divided into three categories as listed in Table 3. The determination between type A and type B was based on whether the heights of the structural parts of the car and truck allowed them to come into contact. Type C was assumed to be present in 25% of the cases, regardless of vehicle size.
The frame height of heavy trucks is exceeds the great majority of LM heights, leading to an estimate of 75% of cars undergoing type A deformation. For middle trucks, however, the frame height is equal to the average car LM height, so it is estimated that only 30% of collisions would produce type A deformation.

Table 3.
Deformation mode of bonnet car

Truck	Bonnet car	Object car	Type A	Type B	Type C
Heavy Truck	Passenger Car	3,096,850	74%	1%	25%
	Minicar	924,040	75%	0%	25%
Middle Truck	Passenger Car	3,096,850	31%	44%	25%
	Minicar	924,040	30%	45%	25%

The probability of unnderrun was presumed to be equal to the probability of type A deformation, since underrun is seen in this deformation mode
Figure 18 presents the results of calculating the contribution rate of FUPDs. Figure 18 (a) plots to the fatality rate of car drivers at each relative speed. The relative speed is calculated by adding the speed of the object vehicle to that of the opponent vehicle.

The speed required to reach 100% collapse rises by 25% after an FUPD is equipped in the test results with 50% overlap. The fatality rate of car drivers when all trucks were equipped with FUPD was estimated by increasing the relative speeds by 25%.
The fatalities were estimated by multiplying the number of accidents at each relative speed by the fatality rate as seen in Figure 18 (b). Using this method, the total number of fatality reductions due to the FUPD equipment was calculated to be 61% of the whole. This ratio was thus assumed to be the contribution rate of equipping FUPDs.

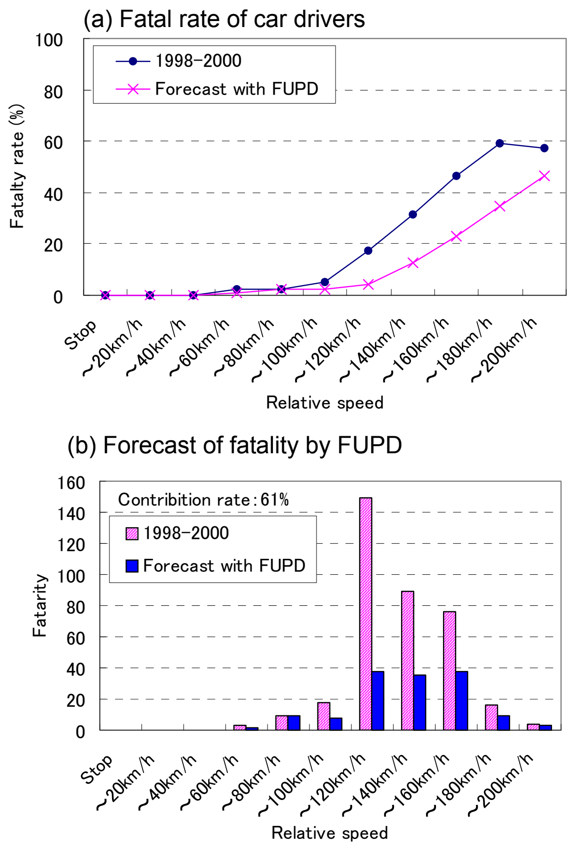


Figure 18. Calculating contribution rate of FUPD (bonnet car vs. heavy truck).

Similar calculations were performed for other forms of accidents with calculated the FUPD effects as listed in Table 4. FUPD fatality reduction in car vs. heavy truck collisions is about 50%. This forecast corresponds to the forecast obtained using in-depth data.
The number of fatality reductions due to FUPD was calculated from these results as illustrated in Figure. 19. Half of the fatalities were to non-belted drivers. Equipping heavy trucks with FUPD could reduce fatalities of belted drivers by 36 fatalities per year (45%). Equipping middle trucks with FUPDs could reduce fatalities by 7 fatalities per year (20%). Similar decreases in fatalities are expected for other passengers in the impacted cars.

Table 4.
Calculation of the FUPD effect

Truck	Bonnet car	Probability of underrun	Contribution rate	FUPD effect
Heavy Truck	Car	74%	61%	45%
	Mini-car	75%	56%	42%
Middle Truck	Car	31%	68%	21%
	Mini-car	30%	59%	17%

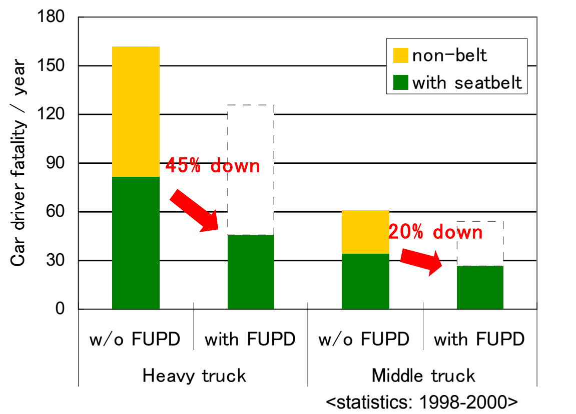


Figure 19. Fatality reductions of car drivers due to FUPD.

FUPD Effect on Cement-mixers and Dump Trucks

Meetings to formulate the FUPD regulations have been underway since 2002. One agenda item at these meetings was allow to admit cement-mixers and tipper trucks to be excluded from application of FUPD regulations. Some countries in Europe exclude tipper trucks because FUPDs interfere with the truck's driving performance of the trucks.

The bumper ground clearance of cement-mixers and tipper trucks in Japan is over 500mm. Equipping FUPDs on these trucks would cause a problem when driven off-road due to a performance decrease. However, it is still necessary to equip tipper trucks with FUPDs since these trucks are often driven on urban roads.

We again calculated the probability of car underrun from the height of the LM. Figure 20 plots the relation between "ground clearance of FUPD" and "probability of underrun". The probability was judged as a more sever condition when the FUPD overlapped at least 50mm of the car LM. Type C was assumed to be present in 25% of the cases.

FUPDs with a ground clearance of 400mm could prevent underrun by 65%. Even with an FUPD 450mm in height, underrun could be prevented by 47%.

Some problems in off-road driving performance would still be present even if an FUPD with a height of 450mm were installed. However, we judged that an FUPD height of 450mm would be appropriate for keeping a balance between off-road driving performance and decrease in aggressiveness. Therefore we have eased the FUPD height for tipper trucks (GVW≧8t) from 400 to 450mm

Table 5 presents the results of recalculating the FUPD effect. In this recalculation, we plotted "probability of underrun" along with "probability of preventing underrun" to exclude the probability of underrun occurring even with trucks equipped with FUPDs.

Figure. 21 depicts the predicted death reductions from using FUPDs. This forecast demonstrates the effect of equipping all heavy trucks over 8t FUPDs, using statistics from 2001-2003.

Cargo and van trucks equipped with FUPDs could reduce car-driver fatalities by 40%. Cement-mixer and tipper trucks equipped with FUPDs at a height of 450mm could reduce car-driver fatalities by 28%.

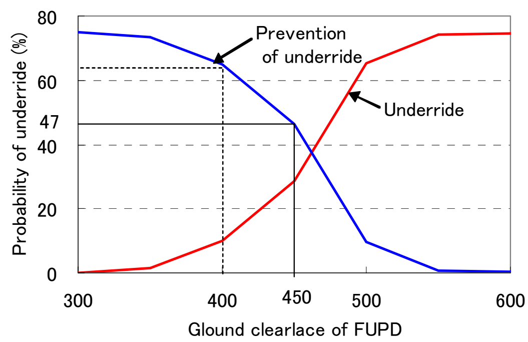


Figure 20. Relation between ground clearance of FUPD and probability of underrun.

Table 5.
FUPD effect (recalculation)

Truck (GVW≧8t)	Ground clearance of FUPD	Probability of preventing underrun	Contribution rate	FUPD effect
Cargo & van etc.	400mm	65%	61%	40%
C-mixer & tipper	450mm	47%	61%	28%

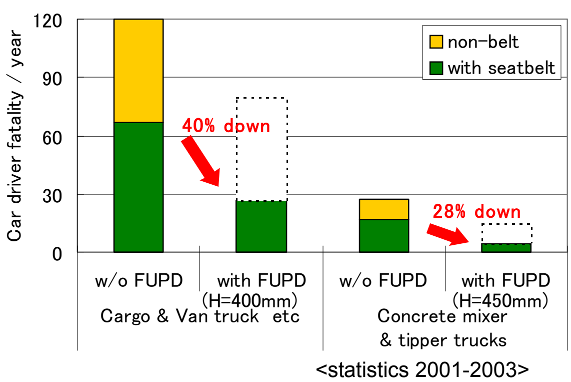


Figure 21. Fatality reductions of car drivers due to FUPD (recalculation GVW≧8t).

SUMMARY

1) Head-on collisions of bonnet-type car vs. truck are the serious accidents in Japan..
2) The car safety performances can work effectively by equipping heavy trucks with FUPDs, and the injury criteria of car drivers would be able to reduced.
3) Equipping heavy trucks (cargo and van) with FUPDs provided under ECE-R93 could reduce car-driver fatalities by 40%.
4) The FUPD height of cement-mixers and tipper trucks was eased from 400 to 450mm representing a ground clearance tat will maintain balanced between off-road driving performance in Japan
5) Equipping heavy trucks (cement-mixers and tipper trucks) with FUPDs could reduce car-driver fatalities by 28%.

Regulations for FUPD equipment in trucks was introduced into Japan in January, 2007. Technological requirements for FUPD are ratified to ECE-R93.

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CRASH TESTS TO ASSESS THE SECONDARY SAFETY OF A LARGE MPV

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ABSTRACT

Multi Purpose Vehicles (MPVs) have gained great popularity for many years. But up to now there are still lacks of published results showing the crash test performance of such vehicles. To assess the secondary safety of the large MPV Mercedes-Benz Viano, DEKRA conducted 3 crash tests according to the Euro NCAP test protocol: a 64-kph-40-%-ODB frontal crash, a 50-kph-MDB side impact and a 29-kph-pole side impact.

The tested model was a 2005 Viano 2.0 CDI Trend with a wheelbase of 3,200 mm and a kerb weight of 2,065 kg. The paper describes the tests and the tested vehicle with its relevant safety features. The test results are shown with special attention to the dummy loads and their assessment including modifiers according to the Euro NCAP protocol. The overall rating of the vehicle is 5 stars for adult occupant safety and 4 stars for child protection. With this background the articles gives also new information on what is state-of-the-art for secondary occupant safety in this vehicle class.

TEST VEHICLE

The crash tests were carried out on a new series Mercedes-Benz Viano, made in 2005, Fig. 1.

The manufacturer offers this six-seater vehicle in 3 versions. The compact variant has a length of 4,748 mm while the long- and extra-long variants have lengths of 4,993 mm and 5,223 mm respectively. The corresponding wheelbases are 3,200 mm for the compact- and long versions and 3,430 mm for the extra-long version. Depending upon the installed engine and equipment fitted, the kerb weight as determined in accordance with DIN 70020 lies within the range 2,020 - 2,195 kg while the gross vehicle mass lies between 2,770 and 2,940 kg.

The particularly popular model 2.0 CDI Trend was chosen for the crash tests, Fig. 2 - the actual vehicle being the long version with a wheelbase of 3,200 mm, an empty weight of 2,065 kg and a gross vehicle mass of 2,770 kg. The total weight of the vehicle when prepared for testing amounted to 2,290 kg for the frontal impact, 2,158 kg for the side-impact with a moving barrier and 2,222 kg for the side-impact on a vertical pole.

Figure 1. Variants of the Mercedes-Benz Viano

Figure 2. Test vehicle Mercedes-Benz Viano 2.0 CDI Trend

The safety equipment of the Mercedes-Benz Viano includes a body with high-strength passenger cell and a support structure capable of accepting very high loads, Fig. 3. This ensures the preservation of the survival space for the occupants in the event of a frontal collision, a side-collision, rear collision and a rollover. Energy-absorbing deformation zones, e.g. in the frontal area, contribute to a low level of loading being imposed upon the occupants.

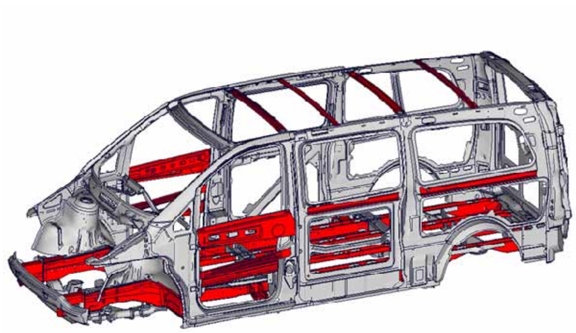

Figure 3. Structure of the body in white

All the seats are fitted with 3-point safety belts. The systems for the driver and the front-seat passenger include a belt tensioner and a belt-force limiter. Front airbags for the driver and the front-seat passenger are provided also in series production models, Fig. 4. Window airbags and thorax airbags can be provided for the driver and the front-seat passenger as optional fittings.

Seat Belt Reminders for the front seats form part of the series equipment for the Viano, too.

Figure 4. Airbags

TEST PROCEDURE

The tests were carried out in accordance with the requirements of the Euro NCAP Test Protocol, (August, 2005 Version) [1].

Frontal impact

In case of the frontal-impact test this takes place at 64.1 km/h with a frontal overlap of 40% with respect to the deformation element (ECE-R 94) on the fully rigid impact block, Fig. 5.

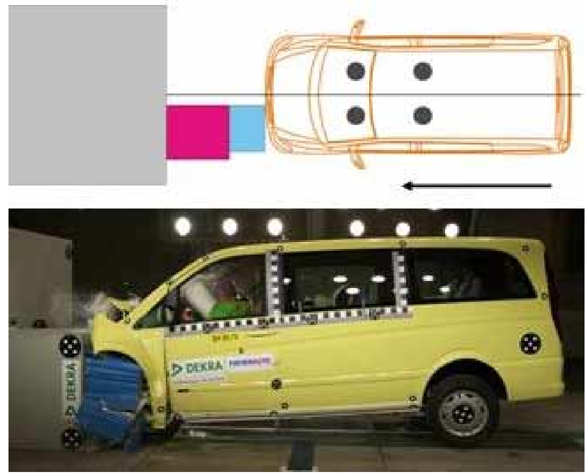

Figure 5. Frontal impact

In this test the vehicle was occupied by an adult dummy Hybrid III, 50th percentile male in both the driver seat and the front-passenger seat. Behind these in the second-row seats were two child dummies, Fig. 6. A P3 Dummy (a 3-year old child) was in the forward-facing seat (Römer Duo Plus) directly behind the driver. Behind the front-seat passenger was a P1 ½ Dummy (a child 1 ½ years old) in a rear-facing child seat (Römer Baby Safe Plus).

Figure 6. Child dummies P 3 and P 1 ½

To measure the deceleration of the vehicle a three-axial sensor was mounted in the lower area of the B-pillar of the vehicle. A further three-axial sensor was mounted on the seat-rails of the second row of seats. Other sensors measured the tensile force in the shoulder belts of the driver and front-seat passenger.

Six high-speed cameras recorded the sequence of motion in the crash test as observed in a horizontal direction from both the left- and the right-hand sides; two high-speed cameras were employed for downward observation recordings and one high-speed camera for upward observation from the filming pit.

Side-impact tests

Moving barrier impact

During the first side-impact test the moveable barrier (with a mass of 944 kg and a deformable front element in accordance with ECE-R 95) impacted the side of the stationary test vehicle at a speed of 50.3 km /h, Fig. 7. As required by the regulations, at the time of the impact the projection of the central vertical line of the barrier met the so-called "R-Point" of the vehicle. The test vehicle was occupied by an adult dummy on the driver side and two child-dummies in the second row of seats. As required by the testing procedure, on this occasion the P3 dummy was behind the front-seat passenger and the P1 ½ dummy behind the driver.

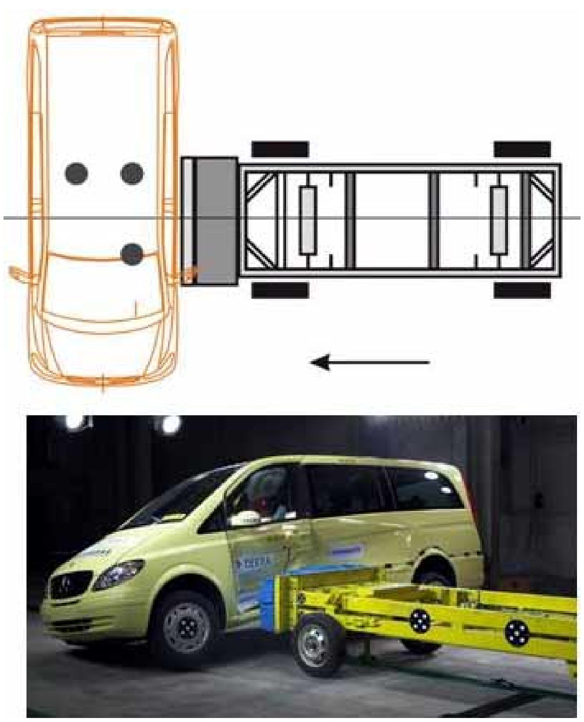

Figure 7. Side impact with moving barrier

As for the frontal-impact test, to measure the deceleration of the vehicle three-axial deceleration sonsors were mounted on the B-pillar and on the seat rails of the second row of seats.

Seven high-speed cameras recorded the sequence of motion during the test as seen from several sides in a horizontal direction. One high-speed camera was used to record what happened in a downward-looking direction.

Pole impact

Since the Mercedes-Benz Viano can be fitted with side airbags for the head as an optional feature, an additional test conforming to the conditions imposed by Euro NCAP was carried out. This involved a side-impact collision of the test vehicle against a rigidly mounted pole (with a diameter of 254 mm), Fig. 8. The impact speed was 29.1 km/h.

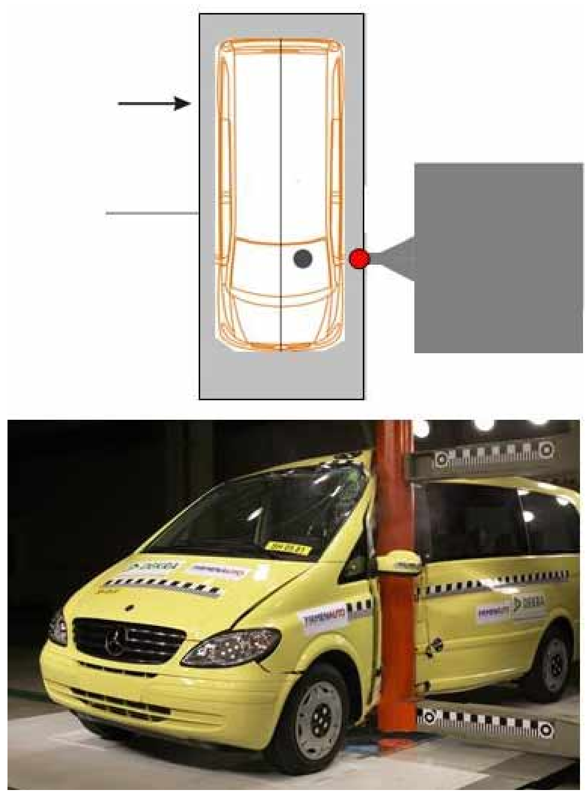

Figure 8. Impact with vertical pole

In the test vehicle the driver was represented by a EuroSid 2 (ES2) Dummy. As required by the conditions prescribed by Euro NCAP the vehicle impacted in such a manner that in the absence of an airbag the pole would have come into direct contact with the head of the driver in the projected direction of its centre of gravity.

In this test also, the measurement of the deceleration of the vehicle was made by three-axial deceleration sensors mounted on the B-pillars and the seat-rails of the second row of seats.

Five high-speed cameras were used to document the movement sequence as seen from several sides in a horizontal direction, one high-speed camera was used for the downward looking recording and another high-speed camera for the upward-looking recording made from the filming pit.

TEST RESULTS

Frontal impact

Fig. 9 shows the test vehicle after the frontal impact. Both front airbags and the belt tensioners for the driver and the front-seat passenger were activated in the manner expected in the event of such a crash. As a result of the deformation caused by the crash the overall length of the left side of the vehicle was reduced by 643 mm while the right-hand side increased in length by 52 mm. In a corresponding manner, the wheelbase on the left-hand side was reduced by 305 mm while on the right-hand side it was increased by 175 mm.

Figure 9. Test vehicle after frontal impact

The A-columns were displaced to only a very slight extent. The survival space for the occupants remained almost entirely intact. Table 1 contains the values for the displacement of the steering wheel, the brake-, clutch- and accelerator pedals in the horizontal- (x), sideways- (y) and vertical (z) directions. No rupture developed in the area of the underbody and splashboard. The bonnet crumpled and did not penetrate into the compartment. During the collision the doors remained closed. After the test the doors could be opened by hand without using tools.

Table 1.
Displacement of steering wheel and pedals

	Steering wheel	Accele-ration pedal	Brake pedal	Clutch pedal
Displacement x [mm]	13	24	59	48
Displacement y [mm]	10	42	2	40
Displacement z [mm]	1	17	42	31

The loads experienced by the dummies in the driver and front passenger seats (both H III) are given in Table 2.

Table 2.
Driver and passenger dummy loads (H III)

Body region	Dummy measured Value	Driver	Pass-enger
	$a_{res, max}$ [g] $a_{res, 3 ms}$ [g] HIC_{36} [-]	51.59 51.01 386	50.0 49.41 396
Neck	F_{shear} [kN] $F_{tension}$ [kN] $M_{retro\ flexio}$ [Nm]	0.26 1.08 7.58	0.27 0.89 8.98
Chest	Compression [mm] VC [m/s]	**33.60** 0.16	**32.73** 0.12
Knee left	Displacement [mm]	0.86	0.67
Knee right	Displacement [mm]	0.90	0.71
Femur left	$F_{compressive}$ [kN]	3.18	2.13
Femur right	$F_{compressive}$ [kN]	2.78	1.62
Lower-leg left	$F_{compressive}$ [kN] Upper Tibia Index Lower Tibia Index	0.74 0.35 0.26	1.19 0.39 0.23
Lower-leg right	$F_{compressive}$ [kN] Upper Tibia Index Lower Tibia Index	0.42 0.29 0.29	1.38 0.28 0.26

With the exception of the chest compression all the measured loads on the dummies lie below the limiting values which are graded by Euro NCAP as the higher performance limits. Therefore, in this instance the best possible (highest) evaluation points (4.00) were awarded for the protection afforded to the two body areas of head and neck as well for the knee, femur and pelvis. The total points for the driver and the front seat passenger thus amounts to 8.00 each.

In Table 2, the loads experienced by the lower legs of the dummies were also below the relevant higher performance limits. In addition, the evaluation of the protection afforded to the occupants in respect of the accelerator pedal displacement on the driver's side was taken into account. Since here, too, no critical values were recorded, the level of occupant protection provided for the body regions of lower leg, feet and ankles was assessed as being the best possible and justifying a points rating of 4.00 each for the driver and the front-seat passenger.

In the case of the chest compression of the driver dummy (33.6 mm) and the passenger dummy (32.73 mm), the Higher Performance Limit of 22 mm was exceeded. In that situation the evaluation points for this body region have to be determined by reference to an appropriate so-called sliding scale. For example, as shown in Fig. 10, the driver dummy receives 2.34 points while his front-seat passenger receives 2.47.

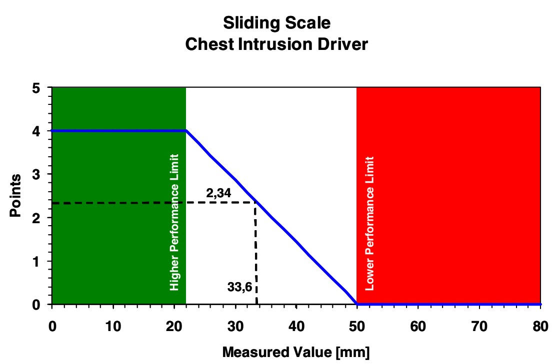

Fig. 10. Assessment of the protection level relating to compression of the driver's chest

This means that the total points scored for protection of all regions of the body of the occupants as assessed by Euro NCAP amounted to 14.34 for the driver and 14.47 for the front-seat passenger compared with a corresponding possible maximum of 16.00.

In the further evaluation procedure specified by Euro NCAP, account was taken of the so-called modifiers. These can lead to a subsequent reduction of the evaluation points initially awarded.

Deductions are made in respect of the head if an unstable airbag contact or an airbag burst is detected by the high-speed cameras. This was not the case in the tests carried out. Consequently the awarded maximal point total of 4.0 actually represents the end-result for occupant protection afforded to the driver and the front-seat passenger.

Where the chest area is concerned, an unstable behaviour of the vehicle structure or contact with the steering wheel and displacement of the A-pillars can lead to a doubled modifier-deduction. Similarly, instabilities in the foot area - for example, a rupture in the floor plate - can lead to a modifier-deduction. None of these situations developed in the tests that were carried out. This means that once again no modifier deduction was necessary. As far as the feet were concerned the awarded maximal point score of 4.00 – as was the case for the driver chest area with a point score of 2.34 and the front-seat passenger of 2.47 – also represent the final result for the overall evaluation of the degree of safety available to the occupants of the vehicle.

A particularly critical view was taken of knee area problems in a collision situation. Medical personnel treating accident victims have reported that in real-life crash situations involving transporters of up to 3.5 t gross vehicle mass, injuries to the lower extremities - characterised by fractures adjacent to the knee-joint as well as direct knee injuries - present a significant problem [2].

The evaluation procedure prescribed by Euro NCAP provides that account be taken of concentrated loads or varied contact conditions involving the knee area of the driver and front-seat passenger in collision situations since these can result in aggravated risks of injury. This means that - although the measured values experienced by the dummies do not reflect a corresponding objective degree of risk - associated modifier-deductions come into play. To be able to assess this factor it is necessary to carry out a detailed analysis of the structure of the vehicle in the knee-impact area, including areas underneath the external panelling. The relevant knee-impact areas for the passenger are illustrated in Fig. 12. The corresponding area for the front-seat passenger is shown in Fig. 11.

As can also be demonstrated by the supplementary sled tests carried out by the manufacturers it is the case that in terms of frontal impact collision situations the structures in the knee-impact area for the driver and the front-seat passenger of the Viano are designed in an exemplary manner for this class of vehicle. Amongst other features, special knee-protection cushions are integrated into the structure supporting the dashboard in order to keep the bio-mechanical loading within acceptable limits in the event of a knee impact.

Figure 11. Front-seat passenger knee-impact areas

Figure 12 Knee support in the driver-knee impact area –visible only after dismantling the panelling

The detailed analysis revealed that no additional risk of injury can be identified for either the outer (right) knee of the front-seat passenger or the outer (left) knee of the driver as well. This confirms the very low level of risk of injury established by the final result of the measured values provided by the dummies.

However, as far as the inner (right) knee of the driver and the inner (left) knee of the front-seat passenger are concerned, the possibility cannot be excluded that in, for example, an oblique frontal impact collision the flexibility of the knee-impact area could limited by the massive support structure lying behind it. Consequently, this lead to a devaluation by one point each.

After rounding off the measured value, the total end-result value for the safety evaluation of the front-seat occupants of the Mercedes-Benz Viano involved in a frontal collision and determined by the Euro NCAP procedure amounted to 13 points, i.e. 81% of the maximal possible value of 16 points. The associated occupant safety-levels in terms of the individual body regions of the driver and the front-seat passenger are displayed by the coloured manikins appearing in Fig. 13.

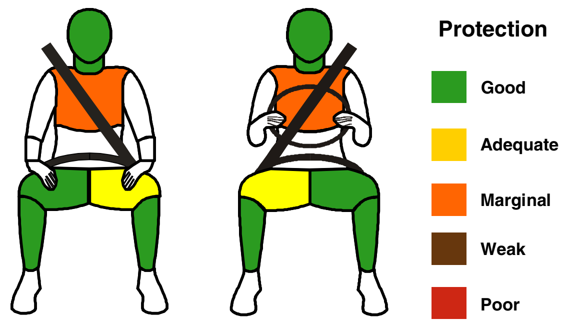

Figure 13. Front impact protection for driver and passenger related to the body regions

Table 3 provides the measured loads experienced by the child dummies during a frontal-impact test.

Table 3.
Child dummy loads frontal impact

Body region	Measured value	Dummy P3	Dummy P 1 ½
Head	$a_{res, max}$ [g]	45.80	34.75
	$a_{res, 3 ms}$ [g]	41.86	**33.44**
	$a_{z, 3 ms}$ [g]	-	**21.29**
	Forward displacement [mm]	400	-
Chest	$a_{res, 3 ms}$ [g]	35.83	28.59
	$a_{z, 3ms}$ [g]	21.22	21.37

The occupant safety level for children in child restraint systems is evaluated in accordance with the Euro NCAP procedure, too. This involves the measured values for dummies together with supplementary criteria for the head and chest. Up to 4 points can be awarded for each of the two body regions, making a possible total of 8.0. In addition, an evaluation of the child restraint system is carried out and based upon the labelling and the degree of secure fixing in the vehicle. This carries a maximal total of 6.0 points.

In terms of occupant safety level, a points total of 4.0 was awarded for each of the head and chest regions of a 3-year old child strapped in a forward-facing Römer Duo Plus child seat. A further 6.0 points were awarded for the child seat itself so that the total number of points awarded matched the best-possible evaluation result of 14.0 points.

On the one hand the dummy measurements, which were all below the relevant higher performance limits, were decisive for this. Furthermore, it was important that the dummy was neither partially not completely thrown out of the child seat and similarly that there was no direct hard contact between the head of the dummy and parts within the inner compartment of the vehicle.

The evaluation of a 1 ½ year old child in a Römer Baby Safe Plus awarded 1.87 points (out of a maximum of 4.0) for the head region because in this case the measured deceleration values were above the relevant higher performance limits. However, the P1 ½ Dummy was also neither partially nor wholly thrown out of the child seat and similarly there was also no hard contact between the head and features within the inner compartment of the vehicle.

With regard to the occupant safety level relating to the chest region, the measured values made on the P 1½ dummy again allowed the maximal number of points to be awarded (4.0). This produced a total of 5.87 points (73% of the maximal 8.0 points). In this case, the securing system was awarded a maximal 8.0 points. Consequently, the overall total of points awarded in respect of the occupant safety level relating to the 1 ½-year old child strapped in the Römer Duo Plus child seat amounted to 11.87 (85% of the possible maximal award of 14.0).

Side impacts

<u>Moving-barrier impact</u>

The condition of the exterior body of the test vehicle following the side-impact collision is shown in Fig. 14.

In the sill area the depth of deformation amounted to 110 mm with respect to the original contour of the vehicle. The most extensive depths of deformation were at a height of 150 mm above the sill level and amounted here to 250 mm.

After the collision, the driver door was jammed. The front-seat passenger door could be easily opened by hand without using any tools. As was to be expected, the collision caused the thorax side air bag and the head air bag to be activated.

Figure 14. Test vehicle after side impact with moving barrier

Table 4 provides the measured loads experienced by the driver dummies (ES2)

Table 4.
Driver dummy loads (ES-2 barrier impact)

Body region	Dummy measured value	Driver
Head	$a_{res, max}$ [g] $a_{res, 3 ms}$ [g] HPC_{36} [-]	10.91 10.73 46
Chest	Compression [mm] VC [m/s] $F_{y, back plate}$ [kN] $F_{y, T12}$ [kN] $M_{x, T12}$ [Nm]	12.25 0.05 0.58 0.47 47.92
Lower body	$F_{res.}$ [kN]	0.26
Pelvis	$F_{pubic symphisis}$ [kN]	0.62

All the measured values lie below the relevant higher performance limits so the maximal 4.0 points could be awarded to the protection level relating to each of the 4 body regions of head and neck, chest, abdomen and pelvis. Consequently, the overall total of the points awarded amounted to 16.0.

The evaluation in accordance with the Euro NCAP requirements of the modifiers to be taken into account with respect to the side-impact barrier collision (ease of door-opening after the collision, the effect of force upon the back plate and the thoracic vertebra T 12, momentum-effect upon the thoracic vertebra T12) did not result in any additional negative consequences. There, the initially awarded total of 14.0 points represents the final result for the evaluation of the occupant safety level for the driver involved in a side-impact barrier collision.

In the context of a child dummy in a side-impact barrier collision only the loadings experienced by the head are relevant. The associated measured values are shown in Table 5. In this case, too, all the values lie below the relevant higher performance limits. This means, therefore, that each dummy receives the maximal awardable points of 4.0 for the head region.

Since no hard contact between the head and features within the internal compartment of the vehicle could be observed, this also represents the overall result. This means that in the event of a side-impact collision the occupant protection level for a 1 ½ year old child strapped in the Römer Baby Safe Plus - and equally for a 3-year old child in the Römer child seat Duo Plus - is evaluated as the maximal possible awardable points, namely 4.0 in each case.

Table 5.
Child dummy loads barrier side impact

Body region	Measured value	Dummy P3	Dummy P 1 ½
Head	$a_{res,\ max}$ [g] $a_{res,\ 3\ ms}$ [g]	21.14 19.86	22.59 22.25

Pole impact

The external damage suffered by the test vehicle after collision with a vertical pole is shown in Fig. 15.

With respect to the original outer contour of the vehicle body the maximal penetration depth by the pole was measured at 392 mm.

When the impact occurred the thorax air bag and the head air bag were activated in the expected manner.

In the evaluation of the occupant protection level by means of this test only the values shown in Table 6 for loadings experienced by the head of the (ES-2) Dummy are definitive.

Figure 15. Test vehicle after pole impact

Table 6.
Driver dummy head loads (ES-2 pole impact)

Body region	Dummy measured value	Driver
Head	$a_{res,\ 3\ ms}$ [g] HPC_{36} [-]	46,78 221

Both values lie below the relevant higher performance level so in this case the maximal awardable points (2.0) can be given. Since the airbag opened in the expected manner there was no reason for a deduction to be made by the relevant modifier.

Overall result of side impact collision tests

In arriving at the overall result, two additional points can therefore be awarded on account of the positive result of the pole-impact test, i.e. to the existing total of 16.0 points awarded for the barrier/side-impact collision. The occupant protection level available to the driver in the Mercedes-Benz Viano in the event of a side-impact collision can thereby be established as the maximal point count of 18.0 as determined in accordance with provisions of Euro NCAP.

The associated occupant protection levels determined for the individual body regions are shown by the coloured manikins in Fig. 16.

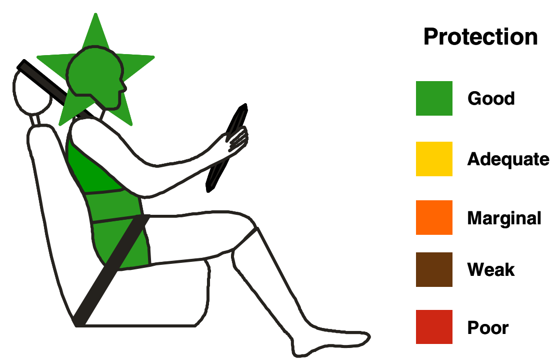

Figure 16. Side-impact collision protection for the driver with respect to individual body regions

VEHICLE ASSESSMENT RESULT

All the evaluation findings made in accordance with the requirements of the Euro NCAP are finally summarised as a single vehicle-related result. For this purpose, the lowest grading, i.e. the lowest number of points awarded for each test and body region defines the overall result, as shown in Table 7.

Seatbelt reminders are provided for the driver seat and the front passenger seat of the Mercedes-Benz Viano and for this reason two additional points are awarded.

Consequently, the vehicle acquires a total of 33 points and this amounts to 92% of the maximal possible 36 points.

On that basis the Mercedes-Benz Viano attains a final star rating of 5 out of a possible 5 stars under the provisions of the Euro NCAP. In other words, the safety of its occupants corresponds to the level offered by modern cars. Taking into consideration the fact that the high weight of the vehicle is equal to that of a van, that outcome is a significantly satisfactory result setting the trend for this class of vehicle.

Table 7.
Overall vehicle assessment result

	Body region	Points driver	Points passenger	Overall result
Frontal impact	Head/ neck	4,00	4,00	4
	Chest	2,34	2,47	2
	Knee, femur, pelvis	4,00	4,00	4
	Lower leg, foot and ankle	4,00	4,00	4
	Subtotal	**13,34**	**13,47**	**13**
Side impact barrier	Head	4,00	-	4
	Upper body	4,00	-	4
	Abdomen	4,00	-	4
	Pelvis	4,00	-	4
Side impact pole	Head	2,00	-	2
	Subtotal			**18**
Seat belt reminder				**2**
Total				**33**

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VOLVO TRUCKS FIELD OPERATIONAL TEST: EVALUATION OF ADVANCED SAFETY SYSTEMS FOR HEAVY TRUCKS

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ABSTRACT

A field operational test (FOT) was recently completed to determine the potential safety benefits of advanced safety systems for heavy trucks. The safety systems in the FOT included a rear-end collision warning system (CWS), adaptive cruise control (ACC), and an electronically controlled brake system (ECBS), which included air disc brakes (ADB). These systems were developed to help reduce the frequency and severity of rear-end collisions, which accounted for 13% of all crashes involving heavy trucks in 2003.

The FOT was funded under the United States Department of Transportation (USDOT) Intelligent Vehicle Initiative (IVI) and was managed by the National Highway Traffic Safety Administration (NHTSA). The industry team that conducted the test was led by Volvo Trucks North America. Battelle performed an independent evaluation of the FOT.

This paper is a summary of the FOT and independent evaluation final reports, and includes the results of safety benefit and benefit-cost analyses based on data collected during the FOT. Driver acceptance, performance, durability, reliability, and maintenance costs of the safety technologies are also reviewed.

INTRODUCTION

This paper summarizes the results of an Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT), as well as an independent evaluation of the FOT, sponsored by the United States Department of Transportation (USDOT).

In September of 1999, the Federal Highway Administration (FHWA) initiated the FOT to determine the potential safety benefits of advanced safety systems on heavy trucks. The National Highway Traffic Safety Administration (NHTSA) managed the FOT, and it was conducted by an industry team led by Volvo Trucks North America, Inc. The team also comprised US Xpress Leasing, Inc., the fleet operator, Eaton VORAD, Eaton Bosch, and the Aberdeen Test Center, as described in [8] Volvo.

The safety systems in the FOT included a rear-end collision warning system (CWS), adaptive cruise control (ACC), and an electronically controlled brake system (ECBS), which included air disc brakes (ADB). These systems were developed to help reduce the frequency and severity of rear-end collisions. According to NHTSA General Estimates System (GES) 2003 data, rear-end collisions accounted for 13% of all crashes involving heavy trucks (including single-unit and combination trucks, GVWR over 10,000 lbs., striking another vehicle).

The objectives of the FOT were:

- Evaluate the performance of the safety systems as operated in a real-world environment
- Accelerate the deployment of the systems

- Help forge strategic partnerships in the transportation industry as a model for public-private cooperation for the development and deployment of advanced transportation safety technologies
- Assess the state-of-the-art in safety benefits analysis for vehicle-integrated advanced safety systems.

Beginning in January 2001, 100 new Volvo tractors were operated in normal revenue-generating service with US Xpress for 3 years throughout the contiguous United States. The trucks were organized into 3 fleets and equipped with the advanced safety systems as shown in Table 1 below.

Table 1.
3 Fleets, Number of Trucks, and Safety System(s) Installed

Fleet	No.	Safety System		
		CWS	ACC	ECBS/ADB
Baseline*	20			
Control	50	✓		
Test	50	✓	✓	✓

*Baseline vehicles were a 20-vehicle subset of the Control vehicles, operated for part of the FOT with the CWS display disconnected.

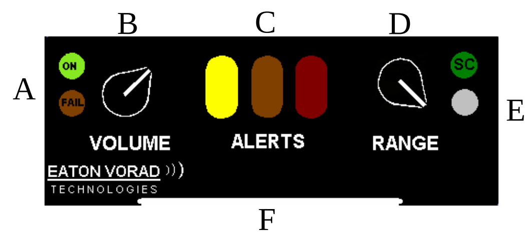
The USDOT contracted with Battelle to perform an independent evaluation of the FOT (see [1] Battelle). Specifically, the goals of the independent evaluation were:

- Estimate safety benefits
- Perform a benefit-cost analysis
- Assess driver acceptance of the new technology.

This paper is a summary of the FOT and independent evaluation final reports. It includes the results of safety benefit and benefit-cost analyses based on data collected from on-board vehicle data acquisition systems (DAS) during the FOT. Data collected from the DAS on each tractor were combined with historical crash data to perform the analyses. A known characteristic of the safety benefit calculation is that the statistical uncertainty of the estimated crash reduction rate varies as the conflict definition changes. For this reason, crash reduction calculations were performed at 3 different levels of conflict severity for 3 combinations of the safety systems. In addition, driver acceptance, performance, durability, reliability, and maintenance costs of the safety technologies are reviewed.

Description of the Technologies

<u>Collision Warning System (CWS)</u> – The commercially available Eaton VORAD® EVT 300 CWS was installed on all 100 of the FOT vehicles. The system transmits and receives radar signals using a forward-facing, front-end mounted radar antenna. The CPU uses the data from the antenna to determine the distance and relative speed between the host vehicle and objects in front. The system provides audible and visual alerts on the display unit (see Figure 1 below) to warn drivers of potentially dangerous situations when other vehicles are within predefined distances or closing times. This gives drivers more time to react and, hopefully, avoid a rear-end collision through avoidance maneuvers.



A: System operation indicators
B: Volume control knob & on/off switch
C: Visual alert indicators & speaker
D: Range setting knob
E: Light sensor
F: Driver ID card slot

Figure 1. Eaton VORAD® Display Unit.

<u>Adaptive Cruise Control (ACC)</u> – ACC utilizes conventional cruise control (CCC) and the CWS forward-facing radar in a combined function. With the system operational, no vehicle in the same lane as the host vehicle, and no target within range of the radar, the system operates like CCC by maintaining a speed set by the driver. If the radar detects a vehicle ahead of and in the same lane as the host vehicle, ACC will maintain a pre-set minimum following interval, expressed in seconds, between the lead vehicle and the host vehicle. The following interval is set using the range knob on the CWS driver display unit (see Figure 1 above). The system maintains the following interval by adjusting vehicle speed via the engine control module, thereby helping the driver avoid a situation that could lead to a collision.

The ACC system installed for this FOT was not capable of actively controlling the vehicle's brakes. ACC operation modes are illustrated in Figure 2 below.

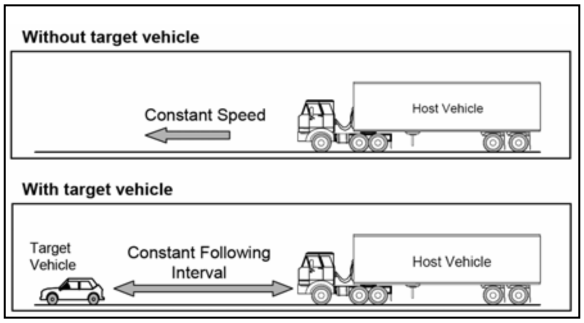


Figure 2. Operation Modes of ACC.

Electronically Controlled Brake System (ECBS) with Air Disc Brakes (ADB) – ECBS builds on existing antilock brake system (ABS) technology in that the air signal traditionally used by ABS to control the activation of the vehicle foundation brakes is replaced by an electronic signal. This reduces the time needed to activate the brakes, resulting in faster vehicle response time and, potentially, a shorter stopping distance. The brake torque generated at each wheel is still provided by air pressure delivered to the brake chamber, but the air pressure is applied and controlled electronically. To provide the brake control redundancy required by current Federal Motor Vehicle Safety Standards (FMVSS 121), ECBS is overlaid on a dual air-brake system, resulting in two pneumatic control circuits and one electronic control circuit (2P/1E). The ECBS used in this FOT was provided by Eaton Bosch.

During both normal and full-treadle emergency braking, ECBS can apply the brake at each wheel individually, providing:

- Improved dynamic brake force distribution, resulting in fewer ABS events and reduced pad wear
- Improved vehicle stability through wheel-by-wheel adjustment of braking in response to real-time conditions
- Improved combination vehicle brake balance and compatibility (if both the tractor and trailer are equipped).

ECBS also has self-diagnostic capabilities including lining wear and brake fade warnings.

The ECBS evaluated in the FOT included a new generation of ADB designed and provided by Volvo. In general, disc brakes are known to generate a linear, stable, and fade-resistant brake torque output. Volvo claims their latest design offers more braking capability, shorter stopping distances, and improved durability and reliability than previous designs. The ADB assembly used in the FOT is illustrated in Figure 3 below. Note that FOT vehicles not equipped with ECBS/ADB were equipped with drum brakes and standard ABS.

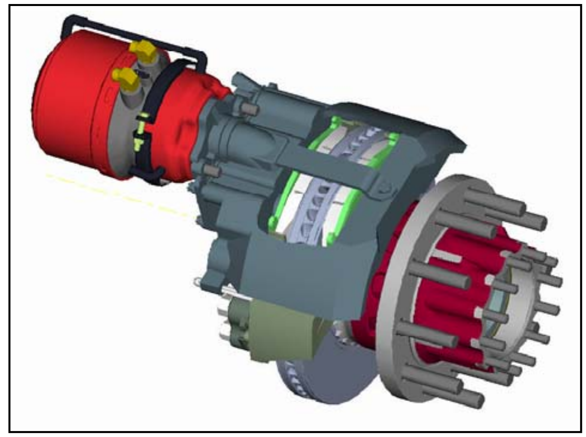


Figure 3. Air Disc Brake (ADB) and Hub Assembly.

On-Board Vehicle Data Collection

The basic locations of the advanced safety systems installed on the FOT vehicles are illustrated below in Figure 4.

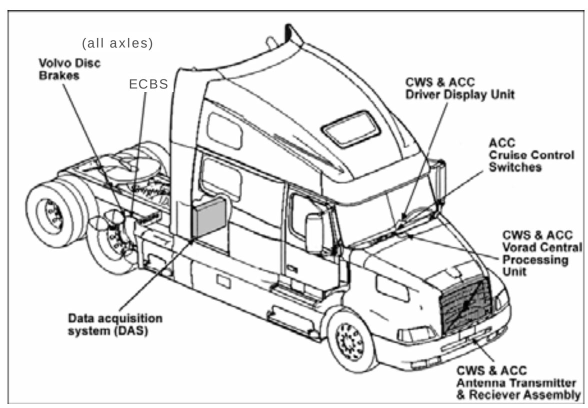


Figure 4. Installation Locations of Advanced Safety Systems and DAS.

Also shown is the location of the DAS, an on-board computer with data collection and communication capabilities. It was used to collect data from:

- J1939 and J1587 vehicle data buses
- VORAD CWS data bus
- Global Positioning System (GPS) sensor
- Steering wheel position sensor
- Biaxial accelerometer (in the DAS).

The data were stored on a solid-state flash memory card and could be transferred to a remote location wirelessly, or by removing the memory card. The data collected were used as inputs to the safety benefits analysis, a summary of which follows.

SAFETY BENEFITS ANALYSIS

The safety benefits of the advanced safety systems were estimated using a statistical model that determined crash rates based on the frequency and severity of rear-end conflicts encountered during the FOT. The fundamental steps involved in this analysis are summarized below.

Data Reduction

Select Conflict Events – During the FOT, data were collected in 15-s time history files when specific trigger conditions were met, creating a triggered event. Conditions which triggered data collection are listed below. Trigger conditions are explained in detail in [8] Volvo.

- Longitudinal deceleration >0.25 g with brakes applied
- Lateral acceleration >0.20 g
- Kinematic motion event (an algorithm which considers lead- and following-vehicle velocity, acceleration, and relative distance)
- Time to collision <4 s
- Following interval <0.5 s
- ABS activation.

Not all triggered events represented a true conflict. These non-threatening events were identified and filtered out of the database. Non-threatening events were defined as those where:

- The lead vehicle was present for <1 s for a stopped lead vehicle, or <2 s for a moving lead vehicle
- The truck was in a curve (yaw rate >2 deg/s for 3 s) and the lead vehicle was stopped or on-coming
- The lead vehicle was in a different lane (lateral distance to target >2 ft)
- The lead vehicle crossed in front of the truck, e.g., at an intersection,
- The lead vehicle was so close to the truck that an unreasonable (>0.4 g) lateral acceleration would be required to avoid a crash
- There was no driver reaction to the event
- The lead vehicle was moving away from the following vehicle after the time of trigger.

Conflict Severity – A driving event recorded in the FOT data was considered a conflict if the event would require a "quick reaction" or "hard braking" maneuver by the driver of the following vehicle in order to avoid a collision with the lead vehicle. Most conservatively, a "quick reaction" was defined as a scenario in which the driver must brake within 1.5 s, and "hard braking" was defined as a scenario in which the driver must brake with a deceleration rate of at least 8 ft/s^2 (0.25 g) to avoid a rear-end crash. If these thresholds were exceeded the event was identified as a "conservative" conflict. If the event did not meet the most conservative threshold, it was discarded.

Three conflict threshold levels were defined in the analysis as indicated below in Table 2. Conflicts that satisfied the medium and aggressive thresholds were actually subsets of the conservative conflicts, since they also satisfied that threshold.

Table 2.
Rear-end Driving Conflict Thresholds

Threshold	Reaction Time (s)	Required Deceleration (ft/s^2)	Percent of Conflicts
Conservative	1.5	8	100%
Medium	1.0	10	24%
Aggressive	0.5	12	7%

In the analysis summarized here, the driving conflicts meeting the conservative threshold above were also required to meet a secondary criterion that they would have resulted in an actual collision if the driver had waited up to 15 s to react (See "Kinematic Analysis for Determining Lag Time" in [1] Battelle). If the driver had waited more than 15 s to react and a collision would not have occurred, the conflict was discarded. This secondary, more-restrictive requirement results in a comparison of more severe conflicts that are more likely influenced by the safety technologies, and therefore an improved safety benefits estimate.

Conflict Classification

After the data reduction steps were completed, the remaining valid conflicts were classified by conflict type. Table 3 below describes the 5 conflict types that are common among rear-end crashes recorded in GES.

Table 3.
Rear-End Conflict Types in GES

Conflict Type	Label	Description*
1	Overtaking Slower Vehicle	Truck is traveling at a constant speed, encounters a slower vehicle (at constant speed)
2	Overtaking While Slowing	Truck is decelerating, encounters another vehicle
3	Changing Lanes	Truck is changing lanes or merging, encounters a slower vehicle (at constant speed)
4	Stopped Lead Vehicle	Truck encounters a stopped vehicle in its lane
5	Slowing Lead Vehicle	Truck is traveling at a constant speed, encounters a decelerating vehicle

*GES does not differentiate between constant speed and acceleration.

These conflict types can also be defined by the kinematic conditions of the lead and following vehicles, as shown below in Table 4. Also shown is the corresponding relative frequency with which each conflict precedes a tractor-trailer rear-end crash recorded in GES, and the conflict percentage determined from analysis of the data collected in the FOT.

Table 4.
Relative Frequency of Conflict Types for Tractor-Trailer Combination Vehicles

Conflict Type	Kinematic Condition*		Relative Frequency	
	Lead Vehicle	Following Vehicle	GES	FOT
1	Constant	Constant	14%	34%
2	Constant/Decel.	Decelerating	4%	30%
3	Constant	Changed Lanes	2%	22%
4	Stopped	Constant/Decel.	40%	7%
5	Decelerating	Constant	26%	7%

*GES does not differentiate between constant speed and acceleration.

As is evident in Table 4, the relative frequencies of conflict types observed in the FOT are significantly different from the relative frequencies of conflicts preceding crashes reported in GES. One obvious reason for this difference is that, unlike the GES relative frequencies, the FOT conflict percentages are not conditional on a crash having occurred. It may be inherently easier to maneuver around a lead vehicle or object when involved in some conflict types, thereby avoiding a crash, and amounting to fewer recorded conflicts preceding crashes in GES.

These differences may also be due to variations in data processing and interpretation of the data. Conflicts defined from GES data are based on information in police reports of actual crashes, while the FOT classification is derived from kinematic criteria applied to time histories. There might also be variability in the definition of the pre-crash movements of the truck. For example, some individuals may define the event by the kinematics of the vehicles immediately before impact, while others define it by the kinematics just before evasive action was taken.

Further, it is possible that the filters used in the FOT data reduction process to remove non-threatening time histories from the pool of driving conflicts were too restrictive for some conflicts, causing valid events to be discarded. If the algorithms were biased towards a particular conflict type, intentionally or not, the recorded number of FOT conflicts could be significantly less.

Finally, it should be mentioned that the amount of FOT data collected for conflicts 4 and 5 was insufficient to complete a proper safety benefits analysis. Considering all of these differences, a decision was made to combine the 5 conflict types defined above into 3 categories as shown below in Table 5. The relative frequencies of the revised conflict categories observed in the FOT data better match the corresponding relative frequencies of conflicts preceding crashes reported in GES.

Table 5.
Re-classification of 5 Conflict Types into 3 Categories

Category	Conflict Type		Kinematic Condition of Following Vehicle	Relative Frequency	
	No.	Description		GES	FOT
1. Constant Speed: Overtaking at constant speed	1	Overtaking Slower Vehicle	Constant	40%	41%
	5	Slowing Lead Vehicle			
2. Slowing: Overtaking while slowing	2	Overtaking While Slowing	Decelerating	44%	37%
	4	Stopped Lead Vehicle			
3. Lane Change	3	Changing Lanes	Lane Change	2%	22%

Safety Benefits Equation

The number of rear-end crashes that occur each year defines the opportunities for crash reduction using any of the advanced safety systems in the FOT. The safety benefits equation (1) is used to calculate the estimated percentage of rear-end crashes that can be prevented by the safety systems. This equation was developed by NHTSA and FHWA, together with the Volpe National Transportation Systems Center (see [4][5][6] Najm and daSilva, [7] Najm). Further, application of (1) to FOT data was considered in [3] McMillan et al.

$$B = \underbrace{N_{wo} \cdot \sum_i P_{wo}(S_i \mid C)}_{\text{Number of relevant crashes (from GES)}} \cdot \underbrace{\left[1 - PR_i \cdot ER_i\right]}_{\text{Percent reduction in crashes for each conflict category}} \quad (1).$$

where $$PR_i = \frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)} \quad (2).$$

$$ER_i = \frac{P_w(S_i)}{P_{wo}(S_i)} \quad (3).$$

For all equations, *wo* indicates a conflict or crash without safety systems installed, and *w* indicates a conflict or crash with safety systems installed. N_{wo} is the annual number of rear-end crashes in a particular fleet, without safety systems installed. S_i (i = 1,2,3) are the 3 rear-end driving conflicts categorized in Table 5. $P_{wo}(S_i \mid C)$ is the probability (without the safety systems installed) that driving conflict S_i precedes a rear-end crash. PR_i is the prevention ratio, and ER_i is the exposure ratio, for driving conflict S_i.

The prevention and exposure ratios are defined by (2) and (3), respectively. $P_w(C \mid S_i)$ is the probability (with safety systems installed) that a rear-end crash occurred, given that driving conflict S_i occurred. $P_{wo}(S_i)$ is the probability (without safety systems installed) that driving conflict S_i occurred.

The prevention ratio, PR, is a measure of the ability of an advanced safety system to prevent crashes after a particular driving conflict has occurred. PR <1 suggests the safety system helps the driver avoid crashes in that type of driving conflict. The exposure ratio, ER, compares the probabilities that a driver will encounter a particular driving conflict, with and without advanced safety systems. ER <1 suggests the safety system helps the driver avoid that type of driving conflict.

The safety benefits calculation is covered in detail in the FOT independent evaluation report ([1] Battelle). The results are presented in the next section.

Percent Reduction in Crashes

The prevention and exposure ratios were used to calculate the percent reduction in crashes (the term $1 - PR_i \cdot ER_i$ in the benefits equation) for each conflict category. The overall percent reduction in crashes was calculated as the weighted average of percent reduction in crashes for each category, using the relative frequency of occurrence of each conflict category in Table 5.

The percent reduction in crashes was calculated for the 3 combinations of safety systems across the 3 conflict threshold levels, as shown below in Table 6. The estimated percent reduction in crashes for each combination of safety systems was determined by comparing the estimated crash rates for drivers who used them with the corresponding rates for drivers who did not. The statistically significant result is shown in bold. A 28% reduction in rear-end crashes is associated with the deployment of the 3 systems bundled together; although the majority of this benefit (21%) appears to come from the effect of CWS.

Table 6.
Estimated Percent Reduction in Rear-End Crashes from Deployment of Advanced Safety Systems at 95% Confidence Interval (Mean ± Two Standard Errors)

Threshold	Selected Safety System(s)		
	CWS	ACC+ ECBS/ADB	CWS+ACC+ ECBS/ADB
Conservative	-1.9 ± 20.8%	9.4 ± 12.4%	7.2 ± 16.8%
Medium	20.7 ± 24.2%	12.0 ± 28.4%	**28.1 ± 21.0%**
Aggressive	25.3 ± 44.0%	9.8 ± 53.6%	29.9 ± 39.6%

These results are also illustrated graphically in Figure 5 below. Statistically significant data are hatched. Note the confidence bounds become narrower as the threshold becomes more conservative. This is because there are more driving conflicts which satisfy the conservative threshold than the medium or aggressive thresholds. This larger sample size leads to tighter confidence bounds in the safety benefits calculation.

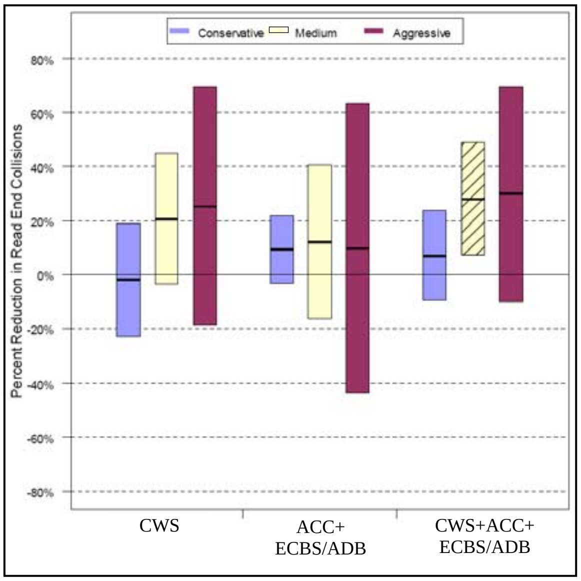


Figure 5. Estimated Percent Reduction in Rear-End Crashes from Deployment of Advanced Safety Systems at 95% Confidence Interval.

Application to Nationwide Fleet

The safety results observed in this FOT were used to estimate the benefits (reductions in crashes, injuries, and fatalities) that could be achieved if the safety systems were deployed on all 1.8 million Class-7 and Class-8 tractor-trailer vehicles nationwide. Data from the GES and the Fatality Analysis Reporting System (FARS) for the 5-year period from 1999 through 2003 were examined to determine the average annual number of trucks involved in rear-end crashes as well as the number of injuries and fatalities. Each year, the approximately 1.8 million tractor-trailer vehicles in the U.S. are involved in 23,000 rear-end crashes, resulting in:

- 12,000 associated injuries
- 304 fatalities.

Because the trucks involved in this FOT were also tractor-trailer vehicles, it is reasonable to project that, if the same safety systems (CWS + ACC + ECBS/ADB) were deployed in the 1.8-million-truck nationwide fleet, each year the technologies could prevent approximately:

- 6,500 rear-end crashes
- 3,400 injuries
- 122 fatalities.

Note that more fatalities are avoided than the 28.1% predicted in Table 6 due to the distribution of fatalities in GES among various conflict types.

Deployment of the CWS alone in the 1.8-million-truck fleet is projected to prevent:

- 4,700 rear-end crashes
- 2,500 injuries
- 96 fatalities.

BENEFIT-COST ANALYSIS

The Volvo IVI FOT independent evaluation team performed a benefit-cost analysis (BCA) to determine the net economic benefits of deploying the advanced safety systems. Following is a general, high-level analysis of all identifiable benefits and all costs at the societal level. The analysis is not targeted specifically to the motor carrier industry, truck manufacturers, or other private-sector entities. The specific hypothesis tested in the BCA is that the total cost to society of deploying and maintaining each of the safety systems is less than the combined value of all the benefits. If the hypothesis is true, the result would be a benefit-cost ratio (BCR)>1, and the deployment of the advanced safety systems would be considered economically justifiable.

Cost Assessment

Costs to deploy and maintain the advanced safety systems include one-time costs and recurring costs, as listed in Table 7 below.

Table 7.
Costs Related to Advanced Safety System Deployment

Cost	Measure
One-Time	Dollar value of capital equipment and software
	Dollar value of initial driver training
	Dollar value of start-up services, installation, consulting, administration, etc.
Recurring	Dollar value of annual operating and maintenance
	Dollar value of new/replacement driver training
	Dollar value of recurring replacement hardware

The quantitative cost information estimated to be incurred during real-world deployment and operation of the safety systems was obtained from the FOT partners and other industry sources. Specific cost information is not included in this paper, but can be found in [1] Battelle.

Cost Savings (Benefits) Assessment

The deployment of the advanced safety systems is expected to result in cost savings by avoiding crashes. No other major cost savings to fleet operators or to society are anticipated. The benefits identified in the analysis are listed below in Table 8.

Table 8.
Cost Savings (Benefits) Related to Advanced Safety Systems Deployment

Benefit	Measure
Safety	Reduced numbers of crashes
	Crash severity
	- Change in severity
	- Effect on injury/fatality rates
	Dollar value of a crash
	Avoided fatalities, personal injury, property and infrastructure damage per crash
	Avoided costs of emergency services (police, fire, EMS) per crash
Mobility	Improved public mobility (reduced traffic delays/congestion from a crash)

It is possible that long-range savings may be realized through enhanced driver satisfaction (resulting in reduced rates of driver turnover and increased savings of funds normally devoted to recruitment, driver training, etc.), reduced insurance rates, and other benefits. These kinds of indirect savings, however, are difficult to quantify and document in an FOT and were not evaluated.

The numbers of crashes, injuries, and fatalities that could be prevented through the deployment of the advanced safety systems were estimated through statistical modeling and analysis based on national historical crash statistics, and also engineering data from the FOT. The costs associated with each crash, injury, and fatality were determined through industry literature reviews.

Two different safety system deployment options (CWS and CWS+ACC+ECBS/ADB) were modeled for all 1.8 million Class-7 and Class-8 tractor-trailer vehicles nationwide across the 3 different conflict severity thresholds (conservative, medium, and aggressive) for 2 different current cost assumptions (low and high), resulting in 12 total scenarios. Both low and high cost assumptions were made due to the wide range in current equipment and installation prices. As might be expected, industry research revealed that prices varied by supplier, manufacturer, amortization volume and timeframe, etc.

Additional scenarios were modeled with potential future reductions in capital and operating and maintenance costs (future low cost assumptions), resulting in 6 more scenarios, for a total of 18. The BCR was calculated for each in year 2005 dollars over a 20-year service window, and displayed graphically in Figure 6 below. As noted before, values of BCR>1 indicate an economic return on investment where deployment of the advanced safety systems could be justified.

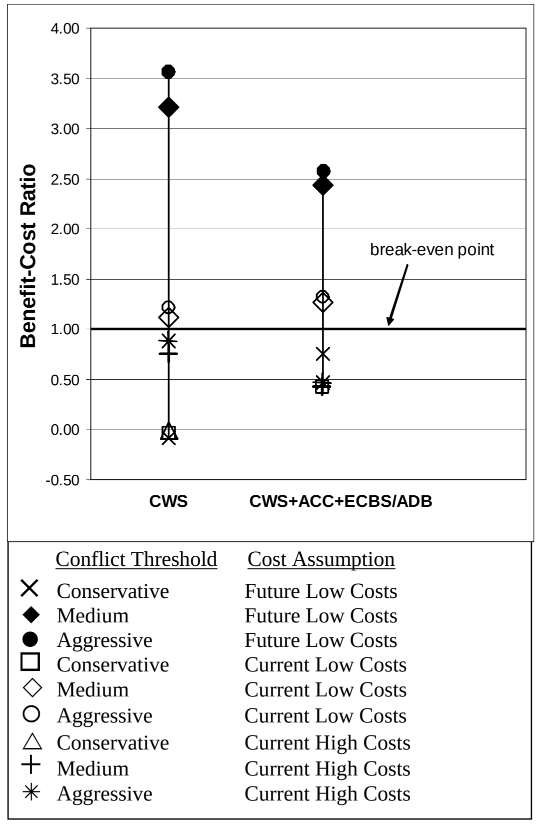


Figure 6. 20-Year Benefit-Cost Ratios Across Nationwide Fleet Using Multiple Cost Assumptions and Conflict Thresholds.

The following observations are worth noting:

- Little difference in BCR was observed between the medium and aggressive conflict thresholds.
- The only positive societal returns on investment occur if CWS or the bundled system is deployed on all tractor-trailers under the current or future low cost assumptions.

USER ACCEPTANCE

According to driver surveys, most drivers agreed that all 3 technologies helped them drive more safely and, as shown in Figure 7 below, most preferred to drive trucks equipped with these systems. Over 80% of drivers preferred trucks equipped with CWS. Many drivers reported that CWS made them more vigilant, helped them maintain a safe following distance, and improved their reaction time and general awareness. Despite a relatively high rate of warnings from non-threatening objects, driver acceptance of CWS was high.

Over 90% of drivers preferred trucks equipped with ECBS/ADB. Drivers said they felt more secure when using the system because they did not have to apply as much pedal pressure to stop the truck. This is because ECBS controls braking using parameters monitoring vehicle deceleration. For a given brake pedal position, vehicles equipped with ECBS decelerate at a fixed rate, regardless of the load on the tractor and trailer. With a conventional braking system, however, the driver must apply more brake pressure to stop a heavier load than what is required for a lighter load. This feature of ECBS avoids the need for drivers to adjust their braking demand as a function of truck load and brake condition. The fade resistance of ADB also contributes to maintaining a constant deceleration rate.

The attitudes about ACC were mixed. About half of those interviewed said ACC helped them maintain safe following distances and improved reaction time. A few drivers reported that ACC made them more relaxed. However, some were uncomfortable with the system taking control away from the driver.

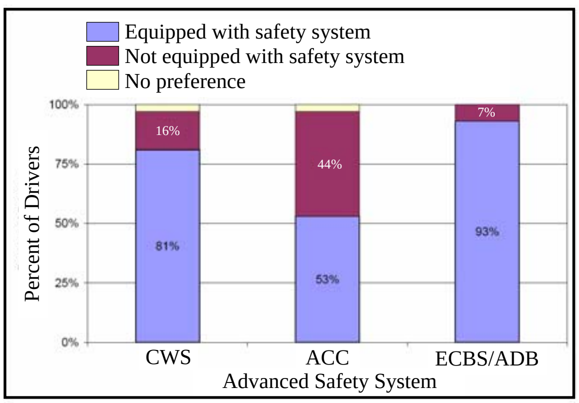


Figure 7. Drivers' Preference for Driving Trucks Equipped with Advanced Safety Systems.

Drivers were generally satisfied with the performance of all 3 systems. Most drivers did not have recommendations for improvements, but of those who did (38%), some wanted more detailed information on CWS indicators (e.g., distances associated with each warning indicator), volume controls for alerts, and better training.

PERFORMANCE SUMMARY

Analyses of the driving conditions under which these systems were used revealed that the systems were most effective at helping to avoid rear-end crashes when the truck was operating at highway speeds. It was found that drivers using CWS tended to maintain greater following distances than drivers without the system, and drivers without CWS warnings experienced more high-closing rate conflicts.

As shown in Figure 8 below, the average following distance for drivers using CWS was approximately 15 ft greater than for drivers without CWS. This finding was supported by the results of the driver interviews (discussed in detail in [2] Battelle.) Drivers using CWS along with ACC and ECBS/ADB had slightly shorter following distances than drivers with CWS alone. This may be due to increased confidence drivers had in their ability to stop with ECBS/ADB; however, there is no data to directly support this theory.

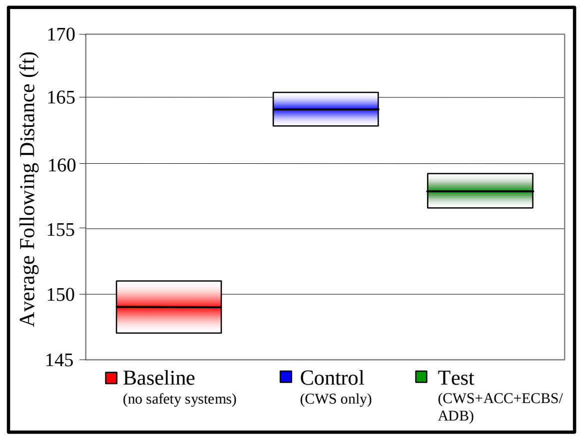


Figure 8. Average Following Distance for Each Fleet.

Baseline vehicles (no safety systems) exhibited an average of 11.9 ABS events per million miles with a time to collision less than 0.5 s. For Control vehicles (CWS only) and Test vehicles (CWS+ACC+ ECBS/ADB), the average number of ABS events was 7.9 and 2.1, respectively. Figure 9 below summarizes this data graphically. The relatively low number of ABS events for Test vehicles suggests that vehicles equipped with ECBS/ADB had a lower rate of ABS activation in hard braking events than vehicles with all-pneumatic systems; however, the effects from ECBS/ADB cannot be isolated from those of ACC in this FOT design.

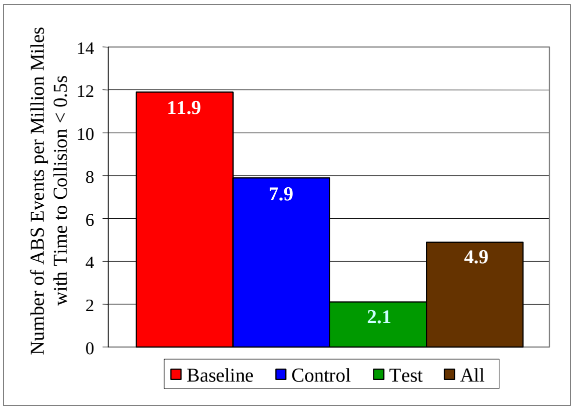


Figure 9. Number of ABS Events per Million Miles with Time to Collision < 0.5 s.

DURABILITY, RELIABILITY, AND MAINTENANCE COSTS

The average frequency of repair for CWS was 0.59 repairs per million miles of travel. Replacement parts for the radar antenna (mounted on the front bumper) accounted for most of the system repair costs, which were $475 on average per million miles of travel.

Brake system repair frequency varied by foundation brake type. The average drum brake repair frequency of 1.31 repairs per million miles was higher than the average disc brake repair frequency of 0.76 repairs per million miles. However, the average disc brake repair cost per million miles ($703) was higher than for drum brakes ($230). This was due to the relatively high cost of pre-production disc brake components and repair technician unfamiliarity with disc brake repair procedures.

The average frequency of repair per million miles was similar for ECBS (1.51) and ABS (1.31). However, the average repair cost per million miles for ECBS ($741) was higher than for ABS ($253) due to the relatively high cost of pre-production electronic control units. Replacement of the wheel speed sensor accounted for the majority of repairs for both systems.

CONCLUSION

During the 3 years of data collection in the FOT there were no major failures of the advanced safety systems. The durability, reliability, and performance of the advanced safety systems were as good as or better than comparable standard systems, demonstrating that they are ready for commercial deployment. The maintenance costs for the advanced safety systems were higher than for comparable standard systems; however, these costs are expected to decrease to a competitive level with higher production volumes.

Deployment of the advanced safety technologies is economically justifiable if CWS or the bundled system (CWS+ACC+ECBS/ADB) is deployed on the nationwide fleet of 1.8 million tractor-trailer vehicles under current or future low system cost assumptions.

A statistically significant, 28% reduction in rear-end crashes associated with the deployment of the 3 safety systems bundled together was found, although the majority of this benefit (21%) came from the effect of CWS.

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Study of Driver Performance/Acceptance Using Aspheric Mirrors in Light Vehicle Applications

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ABSTRACT

Advances in mirror technology have motivated the need for revisiting the question of how drivers use their mirrors while driving. Blind spots are the common complaint of mirrors, and new designs have appeared in the U.S. and European markets to help improve overall visibility. This research involves the study of how drivers perform and accept various combinations of left and right outside planar, convex, and aspheric mirrors. In addition, this research expands the basic design to examine the effect of increasing the vertical dimension of mirrors. This paper reports the work in progress, including the most recent research issues and activities completed just prior to data analysis.

INTRODUCTION

Research and development on automotive rear-view mirrors has been ongoing for many years and has resulted in numerous technical papers, concepts, recommendations, and patents. Many types of mirrors have been developed, but only a few are in common use in light vehicles today. In recent years, a divergence has occurred between mirrors used in the U.S. and mirrors used in the E.U. While the U.S. has stayed with outside rear-view mirrors that are flat or convex, the E.U. has allowed the outside rear-view mirrors to include so-called "aspherics." Other countries and regions have other requirements, but those requirements do not differ too greatly from those of the U.S. or E.U. Thus, there are mainly three types of outside rear-view mirrors in use today: flat, convex, and aspheric.

A flat (planar) mirror is one in which the mirror surface is a plane (within manufacturing tolerances). A flat mirror has the advantage of preserving object size and apparent distance in the virtual image appearing in the mirror.

A convex mirror has a general definition as well as a specific definition. The general definition is that the surface of the mirror protrudes toward the user, and the specific definition is that the mirror surface is spherical (again, within manufacturing tolerances), that is, it has a constant radius of curvature across the entire surface, regardless of direction. Generally, a convex mirror is considered to be spherical in shape unless otherwise stated. A convex mirror minifies the image, that is, it reduces the angular subtense of the image at the observer's eye but it does not otherwise appreciably distort the image until the radius of curvature becomes very small.

An aspheric mirror also has a general definition and a specific definition. The general definition is that the mirror has a complex contour that is neither flat nor spherical. The specific definition is that the mirror is composed of two parts: a convex (spherical) inner portion; and an outer portion that increases in curvature, horizontally (while the vertical radius remains constant). The two portions are separated by a vertical solid or dashed line that is etched into the mirror. The intent of increasing the horizontal curvature of the outer portion is to increase the field of view of the mirror even though some image distortion may occur.

This research has the objective of evaluating and comparing the various outside rear-view mirrors for use in light vehicles. An important goal is to determine the advantages and disadvantages of aspheric mirrors relative to flat or convex mirrors, and then to make recommendations regarding their use. An important additional goal is to determine any age effects that might be involved in the use of aspheric mirrors with particular emphasis on older driver issues.

PROBLEM SIZE

In 2005, there were approximately 6.16 million property damage and injury crashes. Of these crashes, it is estimated that 4.3 million resulted in property damage only, 1.8 million resulted in injury, and there were 43,443 fatalities (NHTSA, 2005). Of the crashes involving only property damage, 4.3% (298,000) were from merging/lane changing maneuvers and 1.4% (96,000) resulted from passing another vehicle. Of the crashes involving injury, 2.3% (61,000) were from merging/lane changing maneuvers and 0.8% (22,000) resulted from passing another vehicle. Of the fatal crashes, 2% (1008) resulted from merging/lane changing maneuvers and 2.1% (1062) resulted from passing another vehicle. These statistics, taken from Traffic Safety Facts, 2005, were obtained from the Fatality Analysis Reporting System (FARS) and General Estimates System (GES) databases. It is quite possible that a lack of visibility in regard to merging, lane changing, and passing may have been an important factor in many of these crashes.

There is evidence that convex mirrors on the driver's side of European vehicles help to reduce crashes. Luoma, Sivak, and Flannagan (1995) examined lane change crashes, related to exterior mirror type, involving light vehicles in Finland. These crashes were reported to Finnish insurance companies between 1987 and 1992. Results from this study suggested that convex and aspheric mirrors on the driver's side reduced crashes during driver's side lane changes by 22%. These results suggest there is some benefit to having non-planar driver's side mirrors.

Similarly, Schumann, Sivak, and Flannagan (1996) examined whether or not convex mirrors installed on the driver's side were of any value. Crash data were examined using a database containing crashes occurring in Great Britain from 1989 to 1992. The results of the study suggested that having convex mirrors on the driver's side of the vehicle did not increase the likelihood of a crash. In some cases (for example, accidents involving mid-size cars) having convex mirrors on the driver's side of the vehicle reduced the probability of a crash.

In a later study by Luoma, Flannagan and Sivak (2000), different from the previously mentioned 1995 study, lane change crashes and effects from non-planar mirrors were examined. Both spherical convex mirrors and aspheric mirrors were examined in this study. A Finnish crash database was used to find lane change crashes between 1987 and 1998. Results suggest that although there was no statistically significant difference between spherically convex mirrors and aspheric mirrors, when compared to planar mirrors, both types of non-planar mirrors reduced the likelihood of a crash by 22.9%. This study supports the findings of previous studies. Moreover, the results from this study are very similar to results from the previous 1995 study. Based on results from the European studies, it appears that there is a benefit to having convex or aspheric mirrors on the driver's side of the vehicle. However, there is no evidence suggesting that one type is better than the other.

REGULATIONS

Regulations in Europe differ from those in the U.S. regarding rear-view mirrors. The Code of Federal Regulations (§571.111), that is, FMVSS No. 111, requires mirrors on both the driver side and interior of a light vehicle. The standard also specifies the types of passenger side mirrors that may be used. The driver side mirror must be planar (unit magnification). The passenger side mirror can be (spherically) convex, thereby providing the driver with an expanded field-of-view. However, the convex mirror must have the phrase "objects in mirror are closer than they appear" imprinted on it. The U.S. regulations do not specifically disallow aspheric mirrors but the mirrors used must meet the existing regulations at the time of vehicle manufacture. One manufacturer, Saab, is known to have used aspherics in the U.S. The mirror is used on the passenger side, has a convex portion, and has a contiguous outer portion that is aspheric. These mirrors have been used on certain models since approximately 1990. The most recent European Directive regarding vehicular rear-view mirrors is 2003/97/EC, "type-approval of devices for indirect vision and of vehicles equipped with these devices" (European Parliament and Council, 2003). This Directive (which specifically defines an aspheric mirror and its use on vehicles) repeals the previous Directive regarding rear-view mirrors on vehicles (71/27/EEC). Both spherical and aspheric mirrors provide a driver with an expanded field-of-view. Directive 2003/97/EC defines an aspheric surface as having a constant radius of curvature in only one plane. The definition for an aspheric mirror is as follows (European Directive 2003/97/EC, section 1.1.1.9.): 'Aspherical mirror' means a mirror composed of a spherical and an aspherical part, in which the transition of the reflecting surface from the spherical to the aspherical part has to be marked. The curvature of the main axis of the mirror is defined in the x/y coordinate system defined by the radius of the primary spherical curvature with:

$$y = R - (R^2 - x^2)^{1/2} + k(x - a)^3$$

R : nominal radius in the spherical part
k : constant for the change of curvature
a : constant for the spherical size and primary spherical curvature.

The primary purpose of the aspheric mirror is to increase the field of view. The current European Directive allows for aspheric mirrors to be positioned on both the passenger side and the driver side of a light passenger car or light truck. These mirrors must have a clearly visible line dividing the spherical portion and the aspheric portion of the mirror.

The current U.S regulation calls for a unit magnification (planar) mirror on the driver's side and a planar or convex mirror on the passenger side if the inside rearview mirror does not meet certain field of view requirements described in FMVSS 111, section S5.3. The planar mirror on the driver's side must provide a reflected field-of-view that is 2.4 m (7.9 ft) wide at 10.7 m (35.1 ft) behind the eyes of the driver.

If a convex mirror is used on the passenger side of the vehicle, it must have an average radius of curvature between 889 mm and 1,651 mm (35.0 in and 65.0 in). The current European directive (2003/97/EC) is different in that the required fields-of-view for the driver's side and passenger side of a light vehicle are identical. The Directive states that the field-of-view provided by the mirror must be 4 m (13.1 ft) wide at 20 m (65.6 ft) behind the eyes of the driver.

RADIUS OF CURVATURE

The current European Directive (2003/97/EC) indicates that all mirrors must be either spherically convex or planar. A spherically convex mirror may have an aspheric portion on the outer edge of the mirror as long as the rest of the mirror satisfies the required field-of-view.

The radius of curvature of a spherically convex mirror must be measured using a three-point apparatus (two outer points bisected by a middle adjustable point). According to Directive 2003/97/EC, all measurements of radius of curvature must be within 0.85 r and 1.15 r, where r represents the nominal radius of curvature. The radius of curvature of the spherical portion may not be less than 1200 mm (42.2 in) and the radius of curvature of the aspheric portion may not be less than 150 mm (5.9 in). These requirements are in addition to the specification on minimum fields-of view.

HUMAN FACTORS OF ASPHERIC MIRRORS

FIELD OF VIEW

The geometrical fields-of-view differences between images reflected from planar mirrors and images reflected from convex mirrors are described in greater detail in a study by Wierwille, Spaulding, Hanowski, Koepfle, and Olson (2003).

Platzer (1995) indicated that an image produced by a convex mirror is smaller than one produced by a planar mirror. Moreover, the image from a convex mirror appears to increase in size more quickly when moving toward the reflection surface than an image from a planar mirror under the same conditions.

An aspheric mirror currently used in the E.U. contains a spherically convex portion that is roughly two-thirds of the mirror. The outer one-third of the mirror is the aspheric portion that is intended to increase the overall field-of-view.

BLIND SPOT REDUCTION

Although the use of exterior rear-view mirrors increases the driver's field-of-view, there still exists a blind zone for mirrors in the U.S. Platzer (1995) addressed the blind zone around the vehicle and discussed remedial strategies. One noteworthy strategy was a concept developed by Volvo in 1979 and later published by Pilhall (1981). This strategy employed the use of a mirror with a decreasing radius of curvature on the outer one-third of the mirror, that is, an aspheric. Because the use of a convex mirror is permitted in the U.S. on the passenger side, the blind zone on the passenger's side is smaller than the one produced on the driver's side. The blind zone produced on the driver's side is large enough to conceal a vehicle in certain positions (Flannagan, Sivak, & Traube, 1999; Platzer, 1995).

According to Flannagan et al. (1999), a driver's direct peripheral field-of-view has a maximum limit of 180 deg when glancing into the exterior driver's side rear-view mirror. During the glance, the driver can see to the rear on the left side, as a result of this 180 deg field-of-view.

Even though the driver's head is turned, the peripheral field-of-view, in addition to the field-of view produced from the mirror, still leaves a blind zone large enough to hide a vehicle.

Flannagan et al. (1999) also indicated that the 180 deg limit was probably smaller for older drivers, thereby resulting in an even larger blind zone. If the field-of-view of the driver's mirror could be expanded to cover 45 deg, then the blind spot would essentially be eliminated provided the driver's peripheral field-of-view was sufficiently useful. The deleterious consequences of using a convex or aspheric mirror on the driver's side would need to be explored, because the image in the mirror is then "minified" by the mirror.

DISTANCE PERCEPTION

Because an aspheric mirror is a convex mirror (in the general sense), the reflected image is changed in terms of size and apparent distance. As the radius of curvature decreases, the image becomes increasingly changed. The apparent size of an object decreases as the radius of curvature decreases, making it appear increasingly farther away. Since convex mirrors change an image, there have been numerous studies examining distance perception using convex rear-view mirrors versus planar mirrors (Flannagan Sivak & Traube, 1997; Flannagan, Sivak, Schumann, Kojima, & Traube, 1997; Flannagan, Sivak, & Traube, 1996; Mortimer & Jorgeson, 1974; O'Day, 1998; Walraven & Michon, 1969). Research has indicated that distance judgments made with planar mirrors are different from estimates made with convex mirrors. On average, drivers will underestimate distance when using flat mirrors. Underestimation is a desirable attribute because it does not increase the likelihood of a collision, i.e., the driver thinks the vehicle is closer than it actually is, and therefore, there is more clearance than is perceived. When drivers estimate distance using convex mirrors, the average underestimation of distance is reduced or eliminated. Since this is an average value, many of the samples will actually involve distance overestimation which can be dangerous. In this case, clearances would be smaller than the driver perceives them to be. Many of the research studies listed above do not explicitly state these general findings, even though the data in the research studies do, in fact, clearly support them.

In research regarding distance perception of large-radius convex mirrors, Flannagan, Sivak, and Traube (1998) concluded that, as the radius of curvature of a convex mirror increased (curvature decreased), the overestimation of distance (as compared with flat mirrors) decreased. However, even the largest radius of curvature (8,900 mm) resulted in a non-dismissible distance overestimation of approximately 8%. Again, this is an over-estimation as compared with the under-estimation that occurs with flat mirrors.

ADAPTATION

Research by Flannagan, Sivak, and Traube (1996) examined adaptation to aspheric mirrors and distance judgments accompanying increased use. The results suggested that increased use of aspheric mirrors decreased distance over-estimation, indicating that drivers adapted to the aspheric mirrors. However, the decrease in distance over-estimation was never as low as that of the planar mirror. This could imply that over-estimation of distance (compared with flat mirrors) will exist for all drivers regardless of how well drivers adapt to the aspheric mirrors.

BINOCULAR DISPARITY

Research by O'Day (1998) suggests that binocular disparity is relatively unaffected by object distance in an aspheric mirror. O'Day used analytical techniques to determine the type of test that should be used to assess binocular disparity. However, his paper does not include tests with actual driver/participants. Consequently, questions with regard to binocular disparity remain unanswered at this time. In O'Day's words,

"It remains to be determined how much disparity is tolerable…, and when the image disparity becomes bothersome. The level of image disparity that causes the driver to see double images needs to be determined".

DISTORTION

It should be recognized that the outer (aspheric) portion of the mirror would be used almost exclusively for presence/absence detection. Consequently, it appears that even though there may be substantial distortions, the mirror can still be used for its primary purpose, namely, object detection. All of the previous research shows similar results. Distance is consistently over-estimated in convex mirrors (as compared with flat mirrors, for which underestimation is the rule). This includes both spherically convex and aspheric mirrors. Flanagan, Sivak, & Traube (1997) provide a summary of previous findings.

RESPONSE TIME AND GAP ACCEPTANCE

There is a trade-off between planar and convex rear-view mirrors. Planar mirrors are believed to provide a driver with accurate (and possibly conservative) distance and speed information but with a relatively small field-of-view. A convex mirror provides a driver with a larger field-of view but with somewhat inaccurate distance and speed information. Which is the better choice for the mirror on the driver's side of the vehicle? One argument in favor of convex mirrors, and also aspheric mirrors, could be response time for object detection.

Helmers, Flannagan, Sivak, Owens, Battle, and Sato (1992) found that responses for object detection were fastest when using an aspheric mirror. Planar, spherically convex, and aspheric mirrors were used in the study to determine object detection time. The planar mirror had the longest detection time. This was in part due to head movements that many drivers use to compensate for the smaller field-of-view. Because the aspheric mirror had a larger field-of-view, object detection took less time. The planar mirror resulted in the slowest average response time (1,676 ms) while the aspheric mirror resulted in the fastest average response time (1,316 ms).

Mortimer (1971) conducted research on lane changing/passing performance of drivers. This study showed that during lane changing maneuvers, gap acceptance judgments were essentially the same for both planar and convex rear-view mirrors, provided that a planar interior rear-view mirror was present. It should be noted that when only exterior rear-view mirrors were used (no interior mirror), gaps judged acceptable were smaller with convex mirrors than with planar mirrors. Also, it was found that in making lane changes, convex mirrors were not viewed more often or longer than planar mirrors during gap judgments. Although this study did not incorporate aspheric mirrors, it does show that when either a planar or convex exterior mirror was coupled with a planar interior rear-view mirror, gap judgments did not significantly differ between the two mirror types. It may be the case that aspheric mirrors result in similar gap acceptance judgments as well. Other studies, such as Mortimer and Jorgeson (1974) and Walraven and Michon (1969), show similar results regarding gap acceptance judgments for lane changing and passing tasks. In the study by Mortimer and Jorgeson (1974) it should be noted that a planar interior mirror was always used in combination with a convex mirror.

A further experiment by de Vos, Van der Horst, & Perel, 2001; de Vos, 2000 examined gap acceptance with planar, spherically convex mirrors, and aspheric mirrors. Using a "last safe gap" method where a car approached from behind in the adjacent lane at a constant speed, the participant was to determine at what point it was no longer safe to change lanes. Also, the participant had to determine the approximate position of the approaching vehicle in the lane adjacent to the driver's side. Results from this part of the study were consistent with those of previous studies. Gaps deemed acceptable for lane changing were larger for planar mirrors than for convex mirrors. Gaps considered acceptable for lane changing via aspheric mirror (with a radius of curvature = 2,000 mm, 6.56 ft) fell between those for planar mirrors and spherically convex mirrors.

According to de Vos (2000), the experiment employed a "worst case scenario" meaning only exterior rear-view mirrors were allowed. This procedure replicated occurrences where interior mirrors may not be available or their field-of-view would be blocked. Future research should examine gap acceptance and detection using planar, spherically convex, or aspheric exterior mirrors used in combination with a planar interior mirror. Acceptable gap information derived from such an experiment may be different from that resulting from using exterior mirrors alone.

EUROPEAN DRIVERS

Research by de Vos (2000) and de Vos, Theeuwes, and Perel (2001) examined European driver experience and knowledge of rear-view mirrors via surveys of mirror types and use. Findings from the studies suggest that drivers are very receptive to having aspheric mirrors on the driver's side of the vehicle. However, one result of the survey was that 46% of the participants did not know that the image produced in a non-planar mirror is modified. Of these respondents, 15% thought that the image is magnified rather than minified. Interestingly, drivers responded similarly for planar versus aspheric mirrors when asked of their ability to judge approach speed of vehicles using the mirror. Overall, the majority of drivers expressed a preference for a nonplanar mirror on the driver's side of the vehicle. Drivers stated that they would choose an aspheric mirror if given the option.

OLDER AND YOUNGER DRIVER DIFFERENCES

Another condition studied by de Vos (2000) was the difference between older drivers and younger drivers. Overall, drivers accepted smaller gaps with convex mirrors than with planar mirrors. This appears to be a result of the minification of the image produced by the convex mirror. Another finding was that older drivers tended to be more conservative than younger drivers, meaning that they tended to wait for larger gaps before deeming them acceptable. The number of glances to the mirror was similar for both older and younger drivers. However, older drivers made more detection mistakes than younger drivers when using the convex mirrors. The opposite was true for detection using planar mirrors, that is, younger drivers made more detection mistakes with planar mirrors.

ACCEPTANCE OF ASPHERIC MIRRORS

If aspheric mirrors were permitted on U.S. vehicles, would these mirrors be accepted by drivers? Research by Flannagan and Flannagan (1998) showed that non-planar mirrors were initially preferred over planar mirrors on the driver's side of the vehicle. This preference for non-planar mirrors also increased after four weeks of use. The study was performed using 114 employees from the Ford Motor Company with either one of two spherically convex mirrors or with one of three aspheric mirrors in place of the planar driver's side mirror. The aspheric mirrors varied in terms of the size of the aspheric portion of the mirror (34%, 40%, and 66%).

Findings from the research suggested that the convex and aspheric mirrors were generally preferred over planar mirrors. The only mirror not as strongly supported was an aspheric mirror with an aspheric portion that was 66% of the mirror surface. Findings from this study, although not exactly representative of the U.S. driver population (because participants were better informed on automotive-related issues than the average driver), may suggest that aspheric mirrors would generally be accepted and would likely increase in acceptance over time. There is a second indication of acceptance; since these mirrors are currently used on the driver's side of many European light vehicles, the acceptability and preference for them is probably satisfactory.

EXPERIMENT

The experiments described herein had two important objectives: assessment of driver acceptance of aspherics and evaluation of gap acceptance for aspherics relative to other types of mirrors that could be used. Since aspherics could be used on the driver's side or the passenger's side, both sides were examined. (There has been very little dynamic testing done on passenger's side aspherics.) Although this paper specifically reports on the dynamic testing only, it is important to note that many other research activities were undertaken in this project including a comprehensive literature review of aspherics in light vehicles, optical and mathematical analyses, and static experimentation.

Information on subjective acceptance was obtained using rating scales associated with two aspects of coordination (with the conventional interior rear view mirror). One of these aspects was "Coordination" and the other was "Speed and Distance Estimation". Four other aspects associated with the given outside rearview mirror itself. These four were "Field of View of the Outside Mirror (by itself)", "Distortion", "Uneasiness", and "Comfort Level". The six aspects taken together should provide an overall assessment of acceptance.

Gap acceptance was obtained for each mirror using the "last safe gap" technique (referred to in this experiment as the last comfortable gap). Last comfortable gap was defined as follows for each subject: Last comfortable gap is the last point where you would feel comfortable changing lanes (with moderate acceleration) to safely move into the lane of the overtaking vehicle. Using a closing speed of 10mph (16.1 km/h), drivers pressed a button at the last instant they deemed it is still safe to accelerate and change lanes in front of an oncoming vehicle. Gap acceptance was also determined by way of one passing and two merging maneuvers. There is the possibility that gap acceptance may be shortened with aspheric mirrors. If so, the magnitude of this shortening needs to be assessed.

MIRRORS INCLUDED IN THE EXPERIMENT

Mirrors included in the road tests were chosen on the basis of several factors. The mirror complement included aspherics that were typical candidates, so that they could be evaluated. In addition, other types of mirrors were also included for comparison purposes.

The driver's side was considered separate from the passenger's side. There are two reasons for this: a given mirror will provide different fields of view depending on the side of the vehicle on which it is installed (Wierwille, Spaulding, and Hanowski, 2005). This is a result of the difference in distance from the mirror to the driver's eyes for the two sides of the vehicle. Also, current U.S. regulations differ for the driver's side and passenger's side mirrors. Consequently, mirrors selected as baselines differed for the two sides of the vehicle. It is important to note that the interior rear-view mirror was made available to all drivers to use in combination with all exterior rear-view mirrors in this experiment.

DRIVER'S SIDE MIRRORS TESTED

Current U.S. regulations require a flat (planar) mirror on the driver's side of the vehicle. Researchers have concentrated on this side in the belief that alternative mirrors would be preferable. In particular, it is widely believed that the advantage of the unit magnification feature of flat mirrors is not as important as the disadvantage of limited field of view. The blind spot created by flat mirrors is believed to create greater risk for the driver. In any case, since a flat mirror is currently required by the regulations, the F-D (flat, driver's side) mirror case was included as the baseline test mirror.

One form of competing alternative is a convex mirror. This mirror has a greater field of view and less nighttime glare. However, it produces some image minification. There are two representative possible alternatives: C20-D and C14-D. The C20-D alternative has a radius of curvature of 2000 mm, producing mild minification and almost twice the field of view of approximately 22.6 degrees. Nevertheless, a substantial blind spot remains. This mirror represents a compromise, having some blind spot reduction and mild minification. The C14-D has a larger field of view of approximately 28.4 degrees and greater minification. This mirror also represents a viable compromise, but still has a blind spot. The two mirrors were considered to be possible alternatives to the flat mirror. They were therefore included in the testing.

Similarly, two aspheric mirrors were included for testing on the driver side. The primary reason for studying aspherics is that they are believed to increase the likelihood of object detection by providing a wide field of view. This can be accomplished with the A20-D aspheric or the A14-D aspheric. The A20-D aspheric has a slightly larger aspheric region than the A14-D, but less minification than the A14-D. Both mirrors represent viable alternatives with large fields of view.

Two additional mirrors were included in the testing for the driver side. Recently, a research study reported that foreground was important in estimating distance to objects (Wu, Ooi, and He, 2004). The gist of the study was that under monocular viewing conditions and uniform field, and when foreground was available to human subjects, they could do a better job of estimating distance to objects. This finding may have ramifications for rearview mirror design for light vehicles. If the mirrors are elongated, they might allow better distance estimation, which in turn could affect gap acceptance as well as understanding of traffic situations. Consequently, two additional new mirrors were tested on the driver side: a flat, elongated mirror designated F-Elongated-D and a convex, elongated mirror designated C14-Elongated-D (with 1400 mm radius of curvature). The mirrors were cut from large van mirrors to fit the research vehicle. It was necessary to cut the lower right corner of each mirror diagonally so that it would not come in contact with the driver's door. The mirrors had dimensions that allowed their entire mirror surfaces to be viewable from the driver's seat, that is, overall, 22.4 cm (8.8 in) high by 15.5 cm (6.1 in) wide. The mirrors combined with a light-weight spacer were attached over the original equipment mirror using hook and loop tape (as was the case for all of the mirrors).

The elongated mirrors provided a view of the pavement closer to the vehicle. In other words, when compared with all of the other mirrors, the driver had a view corresponding to the usual F-D or C14-D mirror, plus a portion of the foreground of this view. Therefore, in total, seven mirrors were tested on the driver side of the vehicle. The mirrors provided exemplars of the various classes, (flat, convex, aspheric, and elongated), thereby allowing direct comparisons across mirror types and characteristics.

PASSENGER'S SIDE MIRRORS TESTED

Current regulations allow for a flat or a convex mirror to be used on the passenger's side. However, industry practice has been to provide convex mirrors on the passenger's side of new light vehicles. Consequently, there are no known new light vehicles with flat mirrors on the passenger's side. The regulations require that if a convex mirror is used, it must have a radius of curvature between 889 and 1651 mm. A brief examination of 60 vehicles in a typical parking lot showed that the mirrors had radii of curvature between 970 to 1460 mm, a range that is clearly inside the current regulations.

Realistically, the baseline mirror should be convex and it should have a radius of curvature within the range actually encountered. The C14-P mirror that was previously tested meets these requirements. Its 1400 mm radius of curvature falls within the range actually used on vehicles. The mirror produces a one-eyed field of view of approximately 21 degrees with good nighttime glare attenuation, but with substantial image minification.

Many vehicles currently have convex mirrors with radii of curvature around 1000 mm. These mirrors meet current U.S. standards, as expected, and are probably used to increase the field of view on the passenger side. Because of these circumstances, it was decided to test such a mirror. To do so, a multi-step process was used. First, a vehicle was found that had a large convex mirror with a radius of curvature close to 1000 mm. Duplicate factory original mirrors were then ordered. The new mirrors were then removed from their backings using a solvent, and finally they were cut to the correct profile using a water-jet machining process. This produced mirrors designated as C10-P that could be used for the experiment.

There were two possible alternative aspheric mirrors for the passenger's side, the A14-P and the A20-P. Both mirrors provide a one-eyed field of view of approximately 35 degrees, and both provide substantial glare reduction in nighttime driving. The A14-P mirror has a convex portion with a radius of curvature of 1400 mm, thus meeting the current standard. In fact, the 1999 to 2001 Saab 9-5 actually uses this mirror, but apparently is unique among cars sold in the U.S.

The A20-P has less curvature in its convex portion, that is, 2000 mm of radius. The A20-P has approximately the same overall field of view as the A14-P, but less image minification in its convex portion. Therefore, it may have a possible advantage in that objects appear a bit larger. The A20-P has a larger aspheric region than the A14-P, so that the total field of view is about the same as the A14-P. Since both aspheric mirrors were considered to be viable candidates, both were included in the road testing. Note that a C20-P was not included on the passenger's side for testing. The reason for this is that it does not seem to have the necessary field of view when used on the passenger's side, and it also falls outside U.S. current regulations. Since drivers now use mirrors with radii of curvature between 889 and 1651 mm and the corresponding fields of view created by them, it seemed undesirable and unnecessary to test such a mirror, which has less curvature.

To account for elongation, one additional mirror was tested. It was designated as a C14-Elongated-P. This mirror had an almost square shape. It did not have as much length as the C14-Elongated-D, because the passenger-side door prevented viewing of the lower portion by the driver. Thus, the mirror was cut to be longer, but it did not extend so far down that the line of sight from the driver's position was obstructed in the lower part. It was deemed undesirable to test a mirror as long as the C14-Elongated-D because such a design would have required complete redesign of the passenger side door in future vehicles. No doubt, such an approach would meet with stiff resistance. The C14-Elongated-P had dimensions that allowed its entire mirror surface to be viewable from the driver's seat, that is, 16.1 cm (6.3 in) high by 17.9 cm (7.05 in) wide. It used a spacer similar to that used for the C14-Elongated-D and the F-Elongated-D, so that the mirror could be aimed using the controls inside the research vehicle.

Similarly, since flat mirrors are no longer used on the passenger's side of light vehicles, and since they have a narrow field of view, they are not viable candidates for modern light vehicles. Thus, the five mirrors selected for testing on the passenger side were the C14-P, the C10-P, the A14-P, the A20-P, and the C14-Elongated-P. These mirrors were believed to represent the most viable candidates for the passenger side of the vehicle.

DESCRIPTION OF MIRRORS

The following descriptions of mirrors were provided to subjects.

Driver's Side

F-D

This mirror has a flat surface. It is like the one you currently have on the driver's side of your own vehicle. Objects seen in this mirror are the same size as when they are seen directly.

This is like a typical mirror in your own home. If you look into it, all objects are correctly sized in the reflection. The field of view of this mirror is relatively narrow. It's possible to miss an object on the driver's side because of the narrow field of view.

C20-D
This mirror has a slightly convex (or spherical) surface. The purpose is to give a somewhat wider field of view than a flat mirror, so there is less chance of missing an object on the driver's side of the vehicle. However, this mirror also makes objects look a little smaller than they really are. If you look into it, all objects are a little smaller, so the scene looks correct but is smaller.

C14-D
This mirror has slightly more curvature than the C20-D mirror. The purpose is to give a wider field of view than a flat mirror (and an even wider field of view than the C20-D mirror), so there is less chance of missing an object on the driver's side of the vehicle. However, this mirror also makes objects look a little smaller than they really are. If you look into it, all objects are a little smaller, so the scene looks correct but is smaller (this mirror makes objects look even smaller than they appear in the C20-D mirror).

A20-D
This mirror has two parts: an inner part that has a slightly convex (or spherical) surface, and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so that there is very little chance of missing an object on the driver's side of the vehicle. However, when looking into the inner (convex) part of this mirror, objects look a little smaller than they really are. Also, when looking into the outer part, objects appear smaller and a little squeezed.

A14-D
This mirror has two parts, just like the A20-D mirror. The two parts are an inner convex portion and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so that there is very little chance of missing an object on the driver's side of the vehicle. This mirror is slightly different than the A20-D mirror. The inner portion is curved more, making objects appear a little smaller. The outer curved portion of the mirror is slightly narrower than the outer portion on the A20-D mirror. As with the A20-D, when looking into the outer part, objects appear smaller and a little squeezed.

F-Elongated-D
This mirror has a flat surface. It is like the one you currently have on the driver's side of your own vehicle, except that it is longer vertically. Objects seen in this mirror are the same size as when they are seen directly. This is like a typical mirror in your own home. If you look into it, all objects are correctly sized in the reflection. This mirror provides a more elongated field of view than a conventional flat mirror for this vehicle. The purpose of this is to provide a view of the ground closer to you, which may help in estimating distances to other objects viewed in the mirror.
C14-Elongated-D
The purpose is to give a wider field of view than a flat mirror, so there is less chance of missing an object on the driver's side of the vehicle. It has the same curvature and viewing effect that the smaller C14-D mirror has, but this one is longer vertically. Its purpose is to provide an elongated viewing area. Just like the F-Elongated-D mirror, the purpose of this mirror is to provide a view of the ground closer to you, which may help in estimating distances to other objects viewed in the mirror. However, because this mirror is slightly convex, it will make objects appear slightly smaller than they actually are.

Passenger's Side

C14-P
This mirror has a convex (or spherical) surface. It is like the one you currently have on the passenger's side of your own vehicle. The mirror is convex to increase the field of view (as compared with a flat mirror), so there is less chance of missing an object on the passenger's side of the vehicle. However, this mirror also makes objects look smaller than they really are, and it is still possible to miss an object occasionally. If you look into it, all objects are smaller.

C10-P
This mirror has slightly more curvature than the C14-P mirror. The purpose is to give a wider field of view than the C14-P mirror, so there is less chance of missing an object on the passenger's side of the vehicle. However, this mirror also makes objects look a little smaller than they really are. If you look into it, all objects are a little smaller, so the scene looks correct but is smaller (this mirror makes objects look even smaller than they appear in the C14-P mirror).

A20-P
This mirror has two parts: an inner part that has a slightly convex (or spherical) surface, and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so there is very little chance of missing an object on the passenger's side of the vehicle. However, when looking into the inner (convex) part of the mirror, objects appear a little smaller. Also, when looking into the outer part, objects appear a little smaller and a little squeezed. (Objects in this

mirror appear slightly larger than in the A14-P mirror.)

A14-P
This mirror has two parts: an inner part that has a convex (or spherical) surface, and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so there is very little chance of missing an object on the passenger's side of the vehicle. However, when looking into the inner (convex) part of the mirror, objects look smaller than they really are. Also, when looking into the outer part, objects appear smaller and a little squeezed. (Objects in this mirror appear slightly smaller than in the A20-P mirror.)

C14-Elongated-P
This mirror has a convex (or spherical) surface. It is like the one you currently have on the passenger's side of your own vehicle. It has the same curvature and viewing effect that the smaller C14-P mirror has, but this one is elongated. The purpose of this mirror is to provide a view of the ground closer to you, which may help in estimating distances to other objects viewed in the mirror. However, because this mirror is slightly convex, it will make objects appear slightly smaller than they actually are.

EXPERIMENTAL DESIGN AND INDEPENDENT VARIABLES

This experiment used 28 subjects for the driver side mirrors and another 20 (different) subjects for the passenger side mirrors. Half of the subjects in each experiment were in the younger age group (younger than 35 years) and the other half were in the older age group (older than 64 years). Within each age group and experiment (side), half the subjects were male and half were female. Thus, the experimental design on the driver side was 2 (age groups) by 2 (genders) by 7 (mirrors) with 7 drivers in each age-gender group. Similarly, the experimental design for the passenger side was 2 (age groups) by 2 (genders) by 5 (mirrors) with 5 drivers in each age-gender group. The mirror variable was the only within-subject variable (for each side of the vehicle).

Runs were counterbalanced, with exact counterbalance correspondence for age and very similar counterbalance for gender. Specifically, for every younger subject there was an older subject with exactly the same order of presentation. On the driver side, the first set of seven younger subjects received exactly the same set of counterbalanced orders as the first seven older subjects. The second set of seven younger subjects used a different set of counterbalanced orders, and the second set of older subjects received this same second set of counterbalanced orders.

For the passenger side, an identical procedure was used. There were, similarly, two sets of counterbalanced orders for five mirrors. The first five younger subjects received the first set of counterbalanced orders, and the second group of five younger subjects received the second (different) set of counterbalanced orders. There was a corresponding older subject for each younger subject.

INSTRUMENTATION

All tests were performed on the Virginia Smart Road in Blacksburg, VA. This is a 2.2 mile (3.5km) long (each direction) instrumented road with a large size turnaround loop at one end and a moderate size turnaround loop at the other end. It is used for research and test purposes, and is closed to the public.

The main instrumentation for this experiment was installed in the experimental vehicle. It included a four-camera video recording system with insert-keyed test condition information, a DGPS distance measuring system, a pushbutton on the right stalk just behind the right side of the steering wheel, and a data acquisition system with an interface to store data as they were gathered.

The twelve test mirrors were prepared. They had any protruding rear components machined away, and they were attached using hook and loop tape over the experimental vehicle's original mirrors in exactly the same way as the previous, static experiments. Elongated mirrors described earlier used a light-weight spacer between the back of the mirror and the attaching tape to allow for the larger mirrors to fit in the smaller mirror housings of the vehicle. Changeover by the experimenter and aiming by the subject was generally accomplished in approximately three minutes.

The camera system served two purposes: to gather eye glance information and to serve as backup in case there was any malfunction of the DGPS distance measuring system. One camera was directed toward the driver's face to pick up glance direction. Two cameras were mounted on the rear package shelf and picked up the image of the confederate vehicle in the adjacent lane. One camera aimed into the driver's side adjacent lane and the other aimed into the passenger's side adjacent lane. The fourth camera was aimed forward and was used to provide a geographic reference to position on the Smart Road in case it was needed. The camera was located in front of the interior rear view mirror, out of the view of the subject. The four camera images were combined using a quad splitter.

The DGPS distance measuring system included an antenna mounted at the top center of the trunk of the subject vehicle. A similar antenna and support system were installed in one of the confederate vehicles. Measurements were initially calculated as distances between the two antenna positions. Corrections were then made for bumper to bumper distances. In all cases, bumper to bumper distances were calculated based on projections to the same lane. In other words, the longitudinal gap was calculated. This was accomplished using the coordinates of the two vehicles (for which gap was calculated), along with the azimuth of the confederate vehicle. Correction was made for longitudinal slope of the Smart Road as well.

Coordination of the three vehicles involved in the experiment was accomplished by voice radio communications with the experimenter in the experimental vehicle serving as the run coordinator (that is, the lead experimenter). The two confederate vehicle drivers were carefully trained ahead of time and were given instructions on the ordering of closing speeds and on the appropriate lanes in which to drive. They were also trained in avoidance maneuvers, in case the subject merged without sufficient clearance. In general, the instrumentation was designed to be unobtrusive. Thus, the driving environment appeared relatively natural to the subject.

DEPENDENT VARIABLES

Both objective and subjective measures were obtained from the experiment. The objective measures were associated with performance of the various tasks. Distances at time of pass or merge initiation and distances at button presses (for last comfortable gap) were analyzed. For each mirror, there were two replications of the pass maneuver and two replications of each of the two merge maneuvers. There were eight replications for the last comfortable gap maneuver. In all cases, units of distance were used for the gaps.

Additional analyses were performed on eye glance behavior during the interval just prior to the passing and merging maneuvers and just prior to button presses. These analyses were intended to indicate the degree to which subjects relied on their interior mirrors and the degree to which they relied on their corresponding outside rear view mirrors, for each of the outside mirrors. In other words, eye-scanning differences among the mirrors were examined. In all cases the interval of 10 seconds just prior to initiation of pass or merge or button press was used for analysis. The reasoning here was that this was the interval during which the driver would be determining whether or not it was safe to perform the maneuver.

The subjective ratings were associated with acceptance of each type of mirror tested. As indicated earlier six ratings were obtained, two involving coordination of the given outside mirror with the interior mirror and four involving only the outside mirror. The last item in the ratings was a questionnaire, which allowed drivers to provide any additional information or suggestions they wished to share. The information and suggestion responses were collected and examined for consensus.

Each rating scale had five descriptor levels and nine vertical delineators. The subject was told to circle one and only one of the vertical delineators, or the line at the halfway point between the vertical delineators. This allowed 17 possible scoring positions for each rating. The ratings were analyzed for differences by statistical tests. Each of the six rating dimensions was analyzed separately as a function of mirror type, age, and gender. The six dimensions, taken as a group were intended to provide a general impression of driver acceptance for each type of mirror, as well as specific elements associated with that mirror. Since there were baseline mirrors for each side of the vehicle, the alternatives could be examined relative to these the baselines.

SUBJECT INSTRUCTIONS AND PROCEDURES

Upon arrival, the subject read and signed an informed consent form, assuming that the subject agreed to participate. The informed consent form provided a general description of the experiment and the subject's duties, the level of risk and discomfort, the length of time he or she would participate, and the compensation to be received. Then, the subject was shown duplicates of the mirrors that would be used on the vehicle. Each mirror was explained to the subject, using the same level of explanation, but pointing out the differences and why the mirrors had been selected for experimentation. The mirrors were described in non-technical terms (see Description of Mirrors section).

It was considered important in these explanations to provide general information on each mirror so that the subjects were informed, but to avoid expressing any opinions as to how well the mirrors might perform. The explanations were deemed necessary, because otherwise, subjects would not have been able to accurately evaluate how well the mirrors performed (all the mirrors had a flat appearance).

The ratings form was also shown and explained to the subject. Showing the form ahead of time gave the subject an indication of what duties he or she would have. Similarly, the passing, merging, and last comfortable gap tasks were explained. The definition of "last comfortable gap" was read to each subject. The experimenter and the subject discussed last comfortable gap until it was clear that the subject fully understood the concept.

After the experimenter answered any other questions, the subject sat in the research vehicle and adjusted the seat and interior rear view mirror. Thereafter, the subject drove to the beginning point for the practice loop on the Smart Road. There, the first outside rear view mirror was attached by the experimenter and aimed by the subject using instructions provided by the experimenter. These instructions included aligning the inside edge of the field of view so that the rear door handle, which was the most extreme lateral protrusion on the vehicle could just be seen at the edge of view. The experimenter then again read the description of the specific mirror being used to the subject. The experimenter then explained the passing and two merging maneuvers that would be performed, indicating that the nominal speed of the confederate vehicles would be 30 mph (48.3 km/h). Basically, the subject accelerated the subject vehicle to pass the two confederate vehicles as the vehicles maneuvered toward adjacent lanes from the near-end loop of the Smart Road. The maneuver was intended to provide a realistic passing scenario in which the mirrors would most likely be used. The first merging followed shortly after in which the subject vehicle was initially ahead of the two confederate vehicles. The subject vehicle then decelerated and merged between the two confederate vehicles, which were again traveling at 30 mph (48.3 km/h). For the second merging scenario, the subject vehicle was initially behind the confederate vehicles in the adjacent lane. The subject vehicle then accelerated and merged between the two confederate vehicles, which were again traveling at 30 mph (48.3 km/h). These two scenarios were intended to exercise the use of the rear view mirrors in typical merging situations. When the end of the outbound leg was reached, the vehicles stopped and then repositioned themselves prior to beginning the inbound leg. The subject was also instructed to use the outside rear view mirror and the interior mirror in performing the maneuvers. It was explained that the first loop was a practice loop. Thereafter, the initial outbound leg commenced.

At the end of the outbound leg, the various vehicles took their correct positions for the inbound leg and initially remained standing. While standing, the subject was told to follow the lead vehicle (which would be traveling at a speed of 30 mph, 48.3 km/h) at the calibration distance of 125 ft (38.1 m) as demonstrated by the standing distance. Note that there were two confederate vehicles. On the inbound leg, one was 125 ft (38.1m) in front of th subject vehicle and served as the lead vehicle in car following. The second confederate vehicle approached in the adjacent lane from the rear and served as the overtaking vehicle. The subject was then instructed to press the stalk button at the last comfortable gap and to use the given outside mirror (in combination with the interior mirror) to assess the last comfortable gap, and that there would be four replications, that is, that the confederate vehicle would approach four times during the inbound leg. When the inbound leg was completed, the vehicles took their positions for the next outbound leg.

At the beginning of the second loop the subject was told that data taking would begin, and except for mirror aiming, the same procedures would be used. Once performance data had been gathered for two loops (end of the third loop for the subject), the subject vehicle stopped and the subject provided ratings for the given mirror. Thereafter, the mirror was changed and the process repeated. Note once again that there was only one practice run and it was at the beginning of experiment (first mirror) for each subject. Thus, all runs had two full loops for data gathering, but only the first run had an additional initial practice loop. Counterbalancing insured that each mirror received the same amount of practice across subjects.

ANALYSIS PLAN

The ratings and performance data will be analyzed by parametric tests and also by nonparametric tests where appropriate. Each of the six rating dimensions will be analyzed separately as a function of mirror type, age, and gender using parametric tests. The six dimensions, taken as a group, will provide a general impression of driver acceptance for each type of mirror, as well as specific elements associated with that mirror. Since there is one baseline mirror for each side of the vehicle, the alternatives will be examined relative to these two mirrors. Performance data will be analyzed in terms of changes in gap. Eyeglance analyses will be used to determine information gathering sources the drivers are using.

CONCLUSIONS

This experiment was set up to provide the data necessary to answer important remaining questions in regard to candidate outside rear view mirrors. In the way of review, these are:

1. Which mirrors, if any, create reductions in gap (clearance) during passing and merging maneuvers, as compared with the mirrors now in general use?
2. Which mirrors, if any, create reductions in last comfortable gap for vehicles approaching from the rear in adjacent lanes?
3. Are there changes in driver visual scan patterns associated with candidate outside rear view mirrors, and if so, what are the implications?
4. What is the degree of initial acceptance (based on six different rating dimensions) of the aspheric mirrors relative to current U.S. mirrors?
5. Which mirrors, if any, from the driver's standpoint are preferred?
6. Does Age affect the performance, eyeglance behavior, or ratings as a function of mirror type?

This experiment was set up to answer these questions using a near-operational, realistic, and safe environment. Test conditions were chosen to exercise the mirrors at the places where they were considered to be most critical. The results of the experiment, combined with the earlier information gathering, analysis, and static tests, should provide the necessary background for making recommendations.

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