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]).

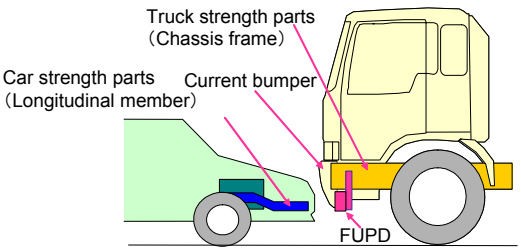


Figure 2. Relative height of front strength parts.

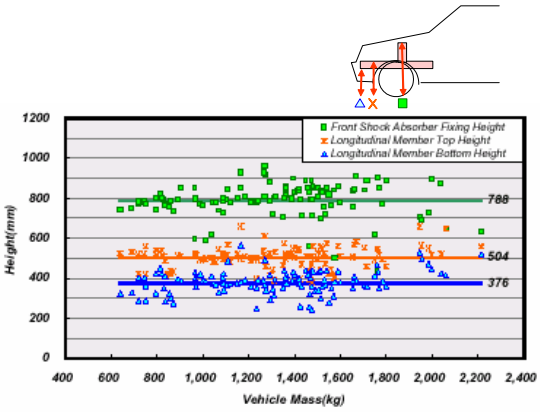


Figure 3. Ground clearance of passenger-car parts (New car registration from 1998; reference cited [4]).

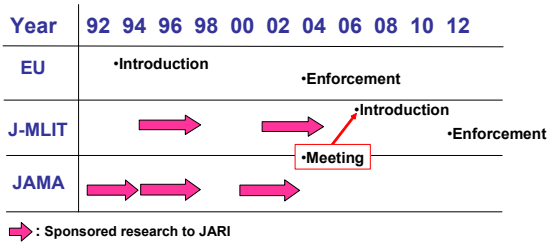


Figure 4. Research for the introducing of FUPD.

CAR-TO-TRUCK ACCIDENTS IN JAPAN

Accident Statistics in Japan

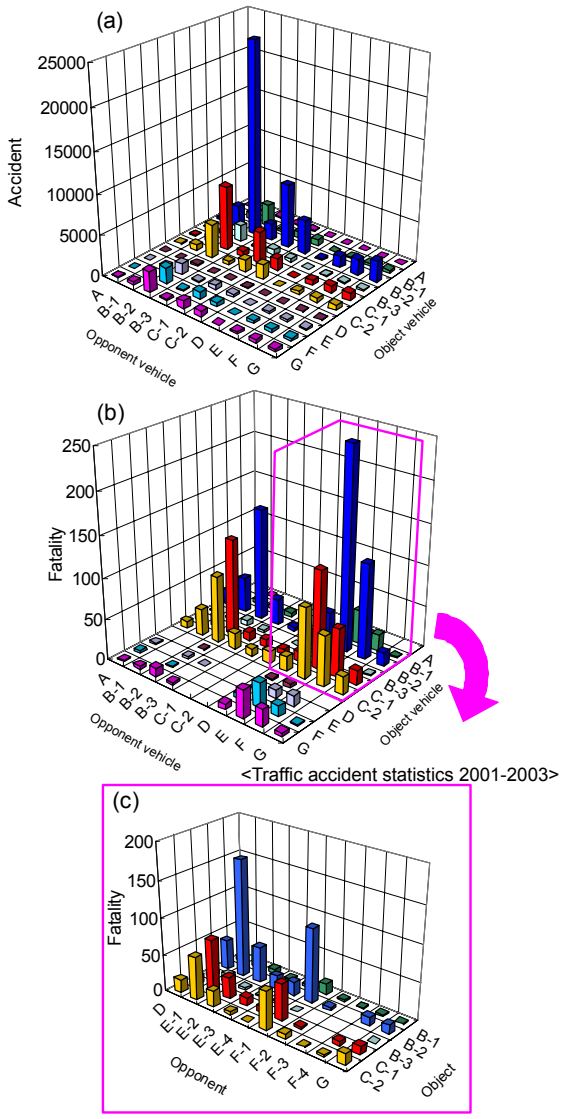
Collisions between cars and heavy trucks represent a serious problem in Japan, where trucks and cars drive together on nearly all roads. Figure 5 displays the vehicle correlations in head-on collision accidents. Figure 5 (a) indicates the number of accidents, and figure 5 (b) indicates the vehicle-driver 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.

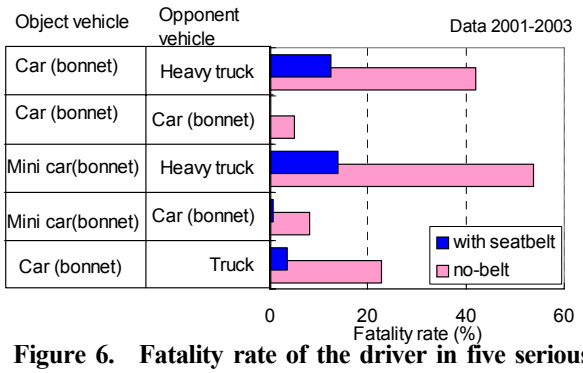


Figure 6. Fatality rate of the driver in five serious accidents according to seatbelt usage.

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.

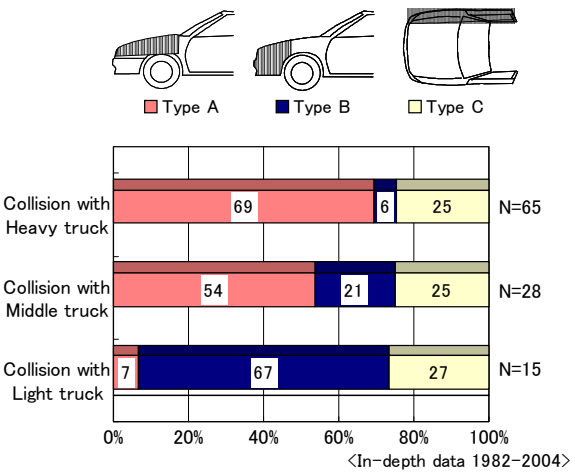


Figure 7. Deformation modes of bonnet cars [3].

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.

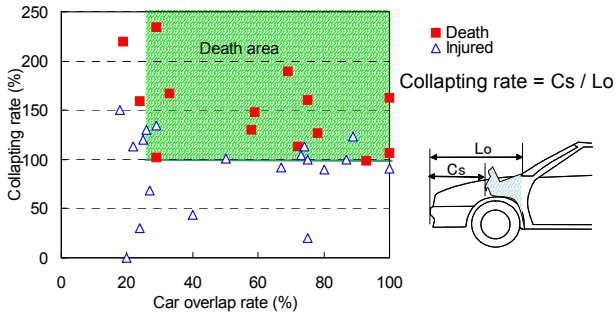


Figure 8. Relation between the car overlap rate and the collapsing rate (driver wearing seat-belt)[3].

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.

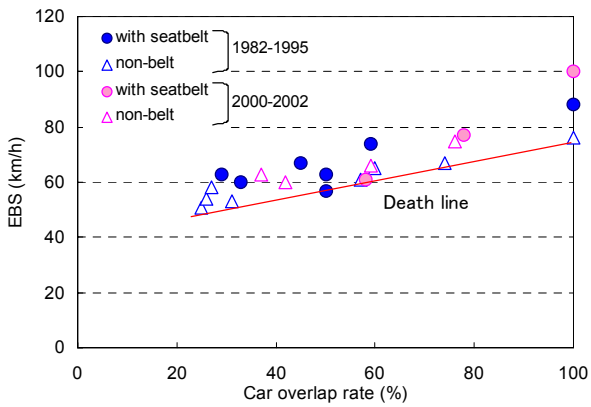


Figure 9. Relation between the car overlap rate and EBS [5].

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.

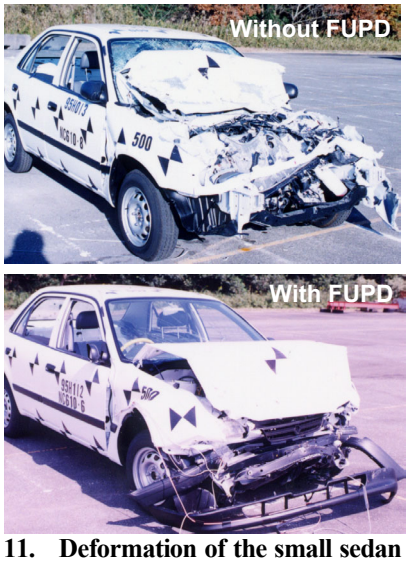


Figure 11. Deformation of the small sedan in 100% collision with the heavy truck.

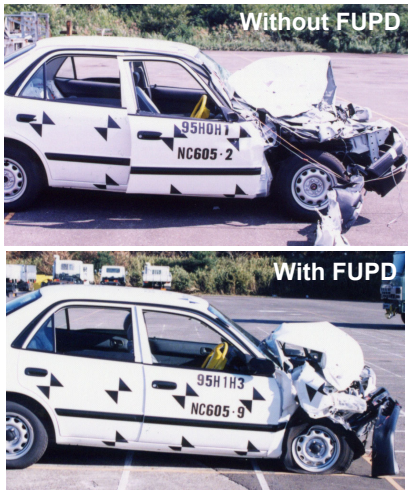


Figure 12. Deformation of the small sedan in 50% collision with the heavy truck.

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 \ 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%		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			

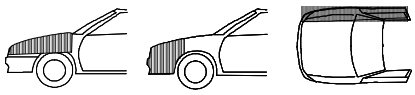


Figure 13 depicts the collapsing rate of crash configurations involving heavy trucks. The collapsing rate exceeded 100% in many cases without FUPD, but was reduced below 100% by equipping the truck with an FUPD. For mini-car collisions, the dummy injury criteria satisfied safety levels even though the 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.

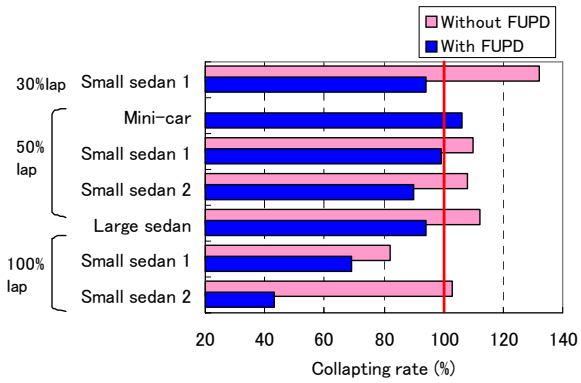


Figure 13. Collapsing rate due to collisions with heavy trucks.

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.

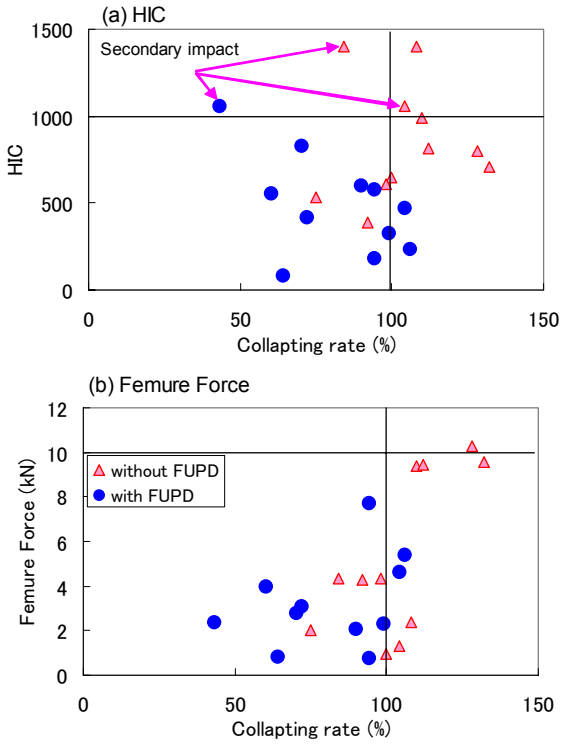


Figure 14. Relation between the collapsing rate and injury criteria

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.

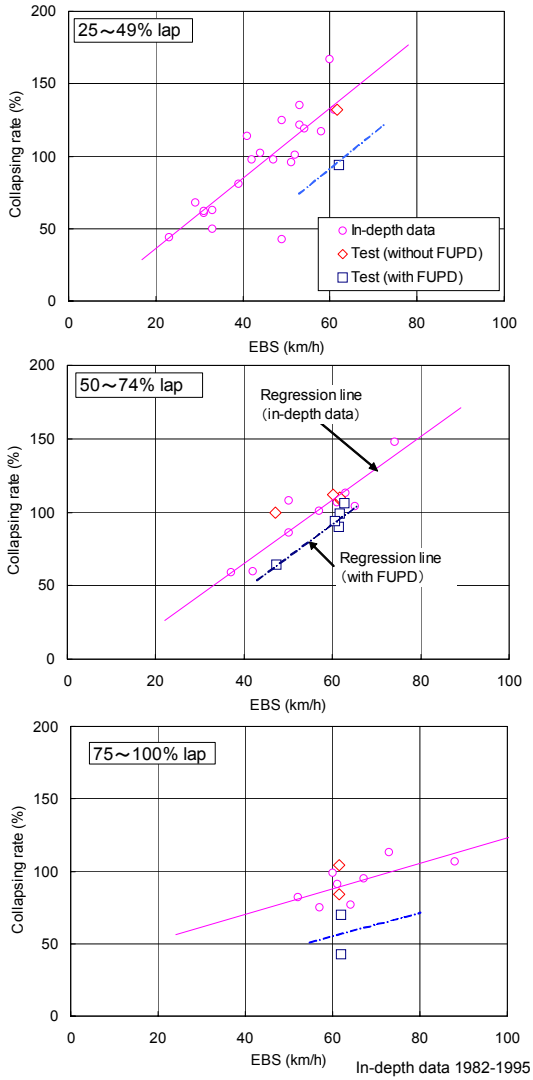


Figure 15. Relation between EBS and collapsing rate.

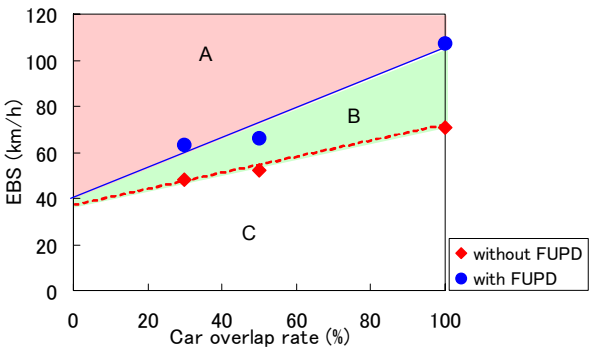


Figure 16. Relation between overlap rate and EBS when the collapsing rate reaches 100%.

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 (%)

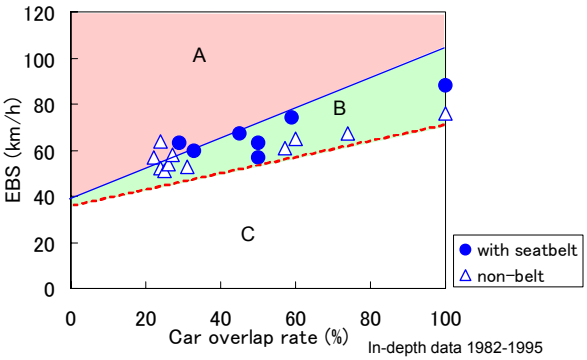


Figure 17. Contribution rate of FUPD.

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.

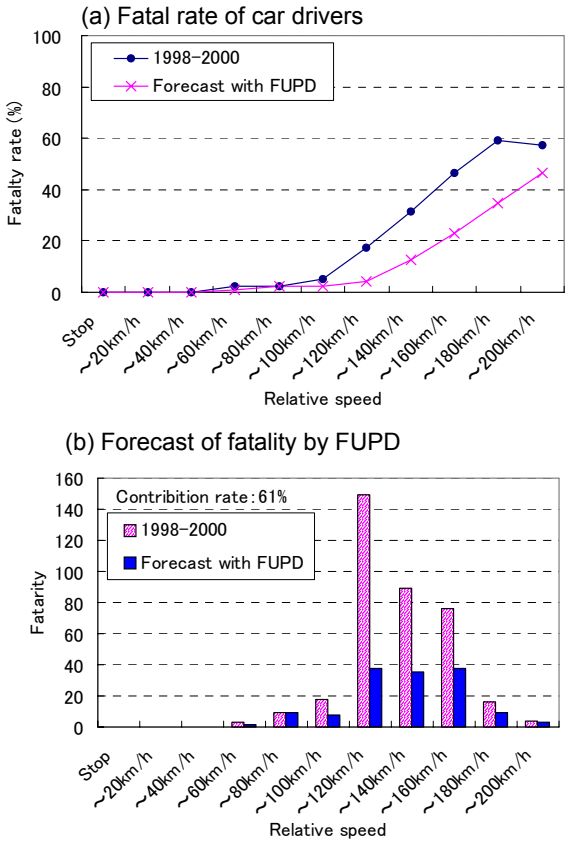


Figure 18. Calculating contribution rate of FUPD (bonnet car vs. heavy truck).

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%

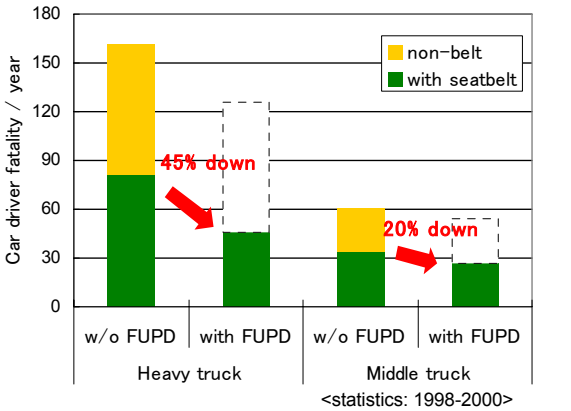


Figure 19. Fatality reductions of car drivers due to FUPD.

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%.

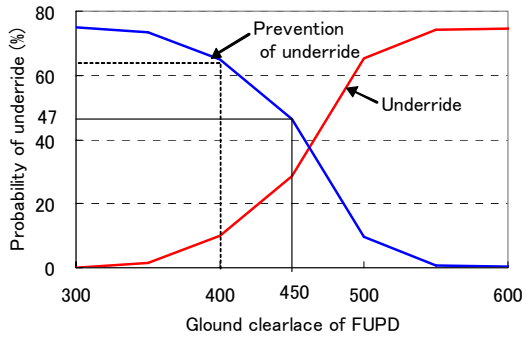


Figure 20. Relation between ground clearance of FUPD and probability of underrun.

Table 5.
FUPD effect (recalculation)

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

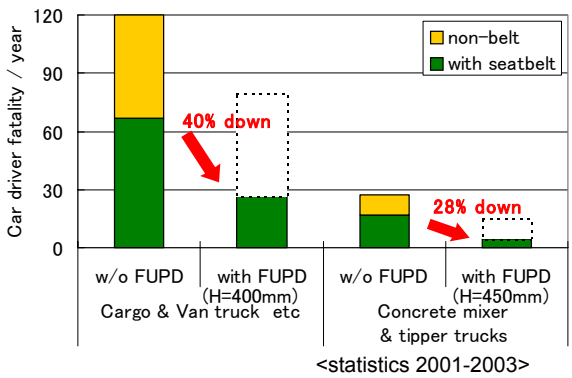


Figure 21. Fatality reductions of car drivers due to FUPD (recalculation GVW≧8t).

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.

REFERENCES

1) Yoshihiro Sukegawa "Real-world accidents of heavy goods vehicles" JARI Research Journal No.27-1, 2005.

2) ECE regulation No.93, 1994.

3) ITARDA "Characteristics of Heavy truck accident" In-depth traffic accident survey & analysis report, 2005 (fiscal year), P505-513, 2006.

4) Hideki Yonesawa, Takeshi Harigae, Yukihiro Ezawa "Japanese Research activity on Future Side Impact Test Procedures", 17th ESV No. 267, 2001.

5) ITARDA "Characteristics of Heavy truck accident" In-depth traffic accident survey & analysis report, 2004 (fiscal year), P452-460, 2005.

6) Yoshihiro Sukegawa "Front underrum protector of heavy truck" JSAE Motor-Ring No. 23, 2006.