EVALUATING THE NEED FOR CHANGING CURRENT REQUIREMENTS TOWARDS INCREASING THE AMOUNT OF LIGHTING DEVICES EQUIPPING SEMI TRAILERS

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ABSTRACT

The report has pointed out the need to provide the truck driver with a semi trailer, the ability to see the contour of the semi trailer and road illumination in the insufficient lighting conditions. The need for equipping the vehicle with additional contour light and lamps illuminating the section of the road overrun by the semi trailer wheels has been assessed.

This is particularly important during manoeuvring with such truck – semi trailer unit at night to ensure safety, as the semi trailer has a different tracking circle than the towing truck. Current regulations are too (categorical) restrictive and limiting possibility of introducing additional lights. The proposal for technically solving this problem as well as amending the regulations, has been presented. The existing technical requirements included in current regulations on lighting do not take into account the need to ensure the visibility of these areas for the truck driver with a semi trailer.
Key words: lighting, semi trailer, visibility, safety.

INTRODUCTION

The analysis of the reasons of collisions and accidents indicates the limited visibility as the essential cause of their occurrence. The tests were made and the drivers driving the trucks with trailers and semitrailers at night were interviewed. It appears from them that on the roads and in the manoeuvring areas which are not lit up by the street lamps, the drivers have the invisible areas on the right and left sides of the vehicle along all its entire length. The reason is the lack of the lighting of the above mentioned areas. If the area is not illuminated by the street lamps, in the darkness they are also not illuminated by the lamps of the own vehicle. Besides these vehicles have unilluminated side edges and they are not visible for their drivers. The driver is unable to observe the shifting of his own vehicle and its position against the other objects, so to avoid the collision or accident.

In Poland at night there are also unilluminated pedestrians on the roads, cyclists, horse carriages etc.

While passing the unilluminated objects, the driver is unable to define the position of the side of the driven truck in relation to the unilluminated objects.

The similar situation takes place when manoeuvres are carried out in none lit up place and there are unilluminated objects either side of the vehicle.

THE ESTIMATION OF THE SITUATION AND CHANGES PROPOSED.

The driver of the vehicle or group of vehicles should have the possibility to observe the surroundings of the vehicle together with the elements of the contour of this vehicle – see Figure 1 [1,2]. The drawing presented below shows these areas around the vehicle.

The driver should have the ability to observe them during driving, both during a day and at night. It should be possible under the street lighting and without it.

The possible directions of relocation of the vehicle were studied: forwards, backwards and sideways. During the day light, the vehicle driver does not receive the direct or indirect visual information transfer from the part of the area surrounding the vehicle, although they are very important for collision free movement. This is a result of obscuring visibility by the none transparent elements of the vehicle cab and vehicle body.

The area not visible around the vehicle at night becomes considerably bigger. The front headlights light the road ahead. The reverse lamps light the road during driving backwards. If there are no street lamps, the rest of the vehicle surrounding (if it does not emit the light itself) is dark. The obstacles that find themselves in these areas are not visible to the driver.

Besides, the vehicle without the trailer while movement around the curve has insignificantly widened corridor of the movement. But the vehicle with the semitrailer moves in the other (wider) corridor than the vehicle without the semitrailer – Figure 2.

During driving round the curves, the wheels of the semitrailer move along quite another track than the wheels of the truck tractor – Figure 3. In this situation at night (without the street lighting) the driver has the unilluminated area, which the wheels of semitrailer run on. Although the driver can look at the mirrors, he cannot see the side of his vehicle;

where and what the wheels of the semitrailer run over [3]. The tractor and semitrailer are not equipped with the lamps which could light up the area which their wheels run over during driving round the curve.

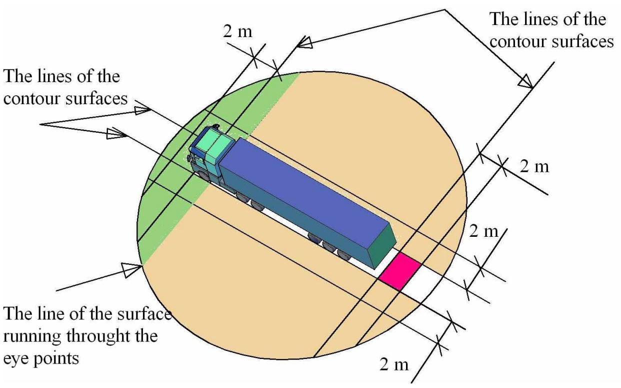

Fig. 1: Extensibility and spacing of the areas around the vehicle which should be seen by the driver

Minimum two typical cases of this situation can be isolated.

1. The driving of the group of the vehicles for example: on the crossing and turning right or left.
2. Avoiding pedestrians or cyclists who move on the road at night and are not illuminated. Additionally at night in the darkness the driver cannot see the side of the semitrailer.

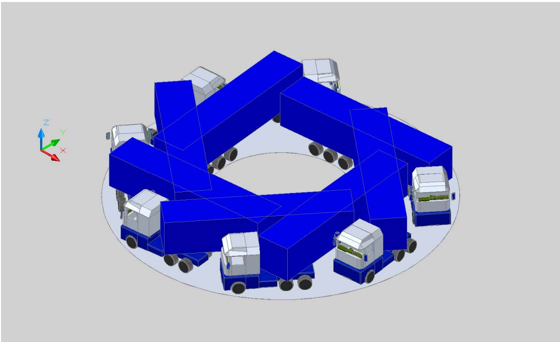

Fig. 2. The tracks of the tractor wheels' movement and those of the semitrailer running around the curve

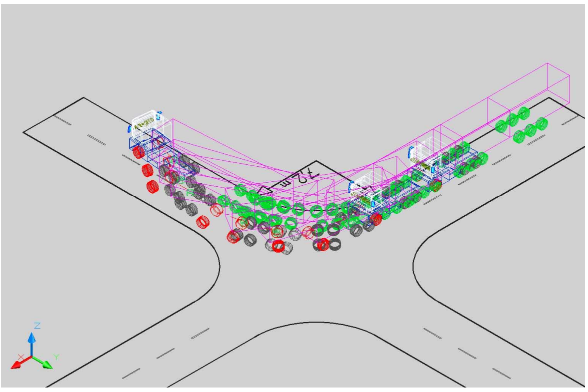

Fig. 3. The movement tracks of the vehicle with semitrailer during turning at the crossing

In the first case, the driver „feeling his way" drives the tractor on around such a curve as to avoid wheels overrunning the kerb or other obstacles. In the second case the situation is similar, but on the narrow road the vehicle coming from the opposite side forces the driver of the group of the vehicles, to return earlier on to his traffic lane. This can cause the collision of his semitrailer with the pedestrian or cyclist who is in the unilluminated area.

The driver is not able to observe the relative position of his vehicle against pedestrian or cyclist. In such a situation, the unilluminated area, in which the collision took place, does not give the driver any information about the accident.

He drives away from the place of the accident, unaware that he should give help. To avoid such a situation, the experiment to select and add the additional lighting of the semitrailer was conducted:

- this additional lighting should show the driver where the contour of the vehicle is – the additional white contour lights,
- the headlamps mounted on the sides of the semitrailer to light the road which the wheels of the semitrailer run on, when the group of the vehicles is moving round the curve.

The fulfilment of these assumptions contradicts the rules of Regulation 48 ECE UN, which are currently in force, regarding this matter, in Europe. The authors of these rules did not take into account the need of more lighting of these areas to enable the driver to watch the road there and see what his vehicle runs over on it.

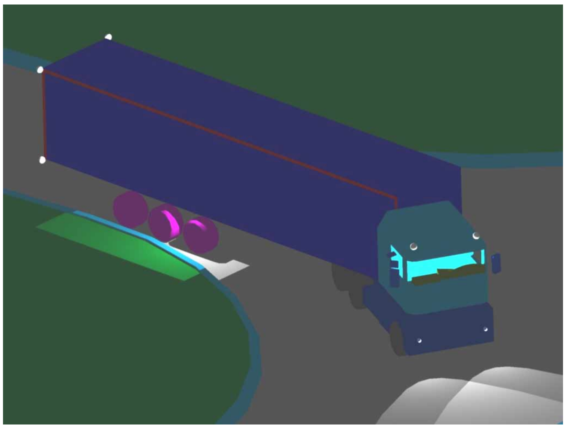

Fig. 4. The view of semitrailer and the placement of the additional lights

In the experiment conducted, the additional white contour lights were used. They were placed at the end of semitrailer, at upper and lower parts. Additionally, the white light was mounted, directed downwards at the road. One lamp being placed on either side of the semitrailer around wheel arches, Figure 4.

Functionally, the additional lamps illuminating the road around the wheels of the semitrailer are connected with the position lights. They are switched on when the position lights are also on. Similarly, the additional contour lights are connected. Photo Figure 5 shows the effect of the additional semitrailer side lighting, on the right hand side, around the wheels.

Additionally, the view of this situation in the darkness is shown, when photos were illuminated by the flash light. When the same area is not lit up by the additional lamp of the vehicle, the driver is not able to observe it in the darkness, during the manoeuvre and to avoid, for example, a pedestrian.

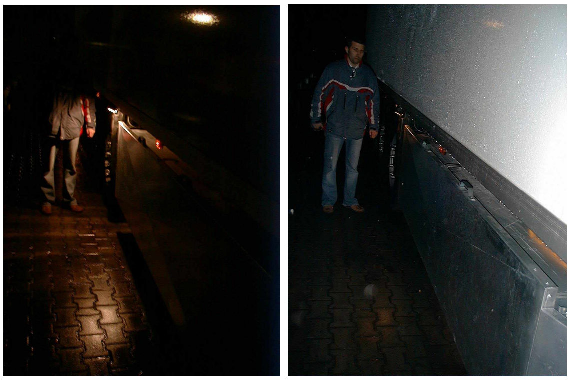

Fig. 5. The photo of the man on the road side, shown in the additional lights of the semitrailer and the view of the same area in the lighting of the flash light

In the light of the gained experiences, actual state of the knowledge, technical progress and the development of the devices for indirect visibility and lighting, it is possible to assist the driver of the group of the vehicles to receive the information from the hitherto invisible areas. In the future, it may be necessary to extend some requirements, concerning the vehicles equipment with regards above mentioned issue.

CONCLUSION AND RECOMMENDATIONS

The aim of these considerations was to obtain the answers to the questions:

- is the need to introduce the additional lighting, justifiable?
- what should it be like
- should this lighting be nonobligatory or obligatory,
- should it be constantly on or only when it is necessary,
- is it necessary to attempt to change the regulations in this field.

The additional lighting in the above mentioned situations is necessary.

To remedy the above mentioned flaw, it is necessary to act for the benefit of the safety system improvement and introduce the additional lighting of the vehicle. It will enable the increase of the areas around the vehicle, which driver should have possibility to observe.

The research programme is being prepared to evaluate this solution in the normal road conditions and to obtain answers to the questions asked.

Problems indicated, allow to understand the scale of the projects with the objective of road traffic safety system improvement. Significant part of these projects may provide measurable effects – decrease of dangers to the population and of serious accidents indicators.

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[3] Regulation no. 46 ECE UN. Uniform provisions concerning the approval of devices for indirect vision and of motor vehicles with regard to the installation of these devices.

[4] Regulation no. 48 ECE UN. Uniform provisions concerning the approval of vehicles with regard to the installation of lighting and light-signalling devices.

THE SEVERITY OF BUS ROLLOVER ACCIDENTS

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ABSTRACT

The most dangerous bus accident is the rollover. An accident statistics - collected by the author containing more then 300 accidents - shows that the average casualty rate is 25 casualties/accident. There are four major injury mechanisms in a rollover which may endanger the occupants: intrusion, projection, total and partial ejection. Different ways of protection may be used to avoid these kinds of injuries, which are shown in the paper. The severity of a rollover accident may be specified on two different ways: one is based on the number of casualties (this is mainly used by the public opinion) and the other one evaluates the circumstances of the rollover (turn on side is less severe than roll down into a precipice) The severity is a basic parameter when specifying the protectable rollover accidents (PRA) in which the occupants may be and shall be protected. This severity limit may be defined on the basis of the accident statistics mentioned above and on the basis of in depth analysis of real world rollover accidents and different rollover tests. These methods are used and discussed in this paper. All bus passengers using different bus categories (traditional buses, high decker tourist coaches, double deckers, and small buses) shall have the same safety level which shall be guarantied by international regulation. This paper is a contribution to the international effort specifying a general regulation about the safety of buses in rollover accidents.

INTRODUCTION

In case of buses the rollover is a rather rare accident type. In Hungary, during a 5 years period (1978-1982) among 1803 bus accidents (as a total) 22 rollovers have been reported [1] this means 1,2%. In this statistics the small buses were not considered. Some other statistics are compared to this figure [2] and the rate of rollover in bus accidents was found in the range of 1-8%. The casualty rate (number of casualties per accident) in rollover accident is around 25 and in frontal collision – which is the second most dangerous bus accident type – this figure is around 17. The difference is even stronger, when comparing the fatality and serious injury rate together: this figure is at least 15 or more, (see Table 5) for rollover and 9 in case of frontal collision.

Since the mid of ’70-s the protection of the passengers in bus rollover accidents is a strong effort in the UN-ECE regulatory work. The existing ECE regulation R.66 – which describes a required strength of the superstructure in a specified rollover test – relates only to large, single deck buses, e.g. the small buses, double deck coaches are excluded from its scope. To define the required protection level for all bus categories, to specify the same (similar, equivalent) safety for all kind of bus occupants, at least the following questions should be analysed and answered:

a) In which kind of rollover accidents (group of accidents) shall be the bus occupants protected? The protection generally means to provide high level probability of survival and to reduce the casualty risk.
b) What are the general requirements to protect bus occupants, to provide the required safety level?
c) How to specify the requirements of the approval (approval test) for all bus categories?

Every bus rollover accident is unique, different from the others. But there are certain regularities which can help to answer on the questions above. Theoretically there are two essentially different rollover processes for buses:

- The bus is rotating around an axis being perpendicular to the vertical longitudinal central plane of the bus. This can happen, if the road has a sharp curve close to a precipice. One accident is known belonging to this type of rollover, happened in Rome, 2005. Only 1-2% of the rollover accidents belong to this type of rollover.
- The bus is rotating around a longitudinal axis being parallel with the main longitudinal axis of the bus. This is the general way of rollover, the so called lateral rollover, at least 98% of the rollover accidents belong to this group. The safety requirements and the approval tests of ECE Reg.66 are based on this type of rollover as it is shown on Fig.1.

This paper – similarly to the international regulatory work – deals only with the second type of rollover. To reduce the number and severity of casualties, the following main injury mechanisms shall be considered:

- **Intrusion**. Due to large scale structural deformations and the loss of the residual space, structural elements intrude the body of the occupants or crash them.

- **Projection.** Due to the uncontrolled movement of the occupants inside the bus, their body impacts the structural parts of the passenger compartment.
- **Complete ejection.** During the rollover process the occupants could be ejected through the broken or fallen windows and crushed by the rolling bus.
- **Partial ejection.** During the rollover process parts of the passenger's body come contact with outside surface and can be strongly scratched or parts of the body (head, arms, chest) get under window column or waist rail and are pressed by it.

Figure 1. Lateral rollover test

CATEGORIZATION OF ROLLOVER ACCIDENTS

To specify those rollovers (rollover groups) in which the passengers shall be protected, the first step is to define characteristics groups of rollovers. The following categories may be used:

a) **Turn on side** ¼ rotation. The bus generally slips a certain distance on its side and finally stops. Level difference is practically 0
b) **Turn into a ditch.** The rotation is between ¼ and ½ .The depth of the ditch is not more than 1,5 m, but it can stop the further rotation
c) **Rollover from the road.** More than ½ rotation, but not more than 2. The level difference between the road and the ground, where the bus finally stops is not more than 10 m.
d) **Serious rollover.** More than 2 rotations. The level difference between the road and the ground, where the bus finally stops is more than 10 m.
e) **Combined rollover.** The rollover is followed by a fire, or before the rollover a severe frontal collision occurred, or after the rollover the bus falls into a river or lake, etc.

Sometimes category "b" (turn into a ditch) is listed either in category "a", or category "c".

Categories "a", "b" and "c" may belong to the protectable rollover accidents (PRA) and it is a realistic public demand to assure high level survival probability for the bus occupants in these kinds of rollover. One of the most important requirements is that in PRA-s the bus superstructure shall have certain strength to avoid its collapse or large scale deformation, to avoid the intrusion type casualties. It has to be mentioned that the 2 rotations and the 10 m level difference in category "c" are not theoretical, but practical figures. There were more real accidents (as well as full scale rollover tests) validating these figures. It is important to emphasize that the approval test specified in R.66 can assure an appropriate strength for the superstructure to survive this type of rollover.

SPECIAL ROLLOVER STATISTICS

Based on the Hungarian media reports (TV and radio new, newspapers, journals, internet, etc.) the collection of information started in 2000 and the results of this work were published many times.

Table 1.
Summary of rollover statistics

Number of accidents	338
Number of countries involved[(1)]	65
Total number of	
- fatalities	4054
- serious injuries	1029
- light injuries	977
- injuries without classification	2594
- reported "many injuries"	21 times
Type of rollover (severity)	
- turned on side	64
- rollover from the road	127
- serious rollover	74
- combined accident	73
Category of the bus rolled over	
- C I. (city, suburban)	7
- C II (intercity, local,	34
- C III (tourist long-distance)	130
- Double decker	16
- Small bus [(2)]	67
- School bus[(3)]	9
- Other (worker, pilgrim, etc.)	8
- unknown	67
Deformation of superstructure	
- serious deformation[(4)]	61
- slight deformation[(5)]	82
- no information	195

Footnotes to Table I.

(1) countries may be involved as manufacturer, approval authority, operator or the scene of the accident.
(2) in the media reports this category is called: minibus, microbus, small bus, midi bus, club bus, ambulance bus, etc. without exact specification
(3) in many cases children, students were transported by normal coaches, these accidents are counted as coach accidents.
(4) serious deformation means the damage of the survival space, (the collapse of the superstructure obviously belongs to this category).
(5) slight deformation means that the survival space very likely is not damaged in the rollover accident.

The last presentation shown and analysed on the last EAEC Congress in Belgrade (2005) was based on 222 rollover accident happened worldwide reported by the Hungarian media [3]. Meantime this statistics has been increased, the new version contains already 338 accidents. Table 1. gives a summary of this statistics analysing the 338 accidents from different point of views.

Table 2.
Rollovers in three major regions.

Regions	Before 2001	2001-2003	2004-2006(3)	Total
Hungary	10	39	45	94
Europe(1)	30	29	32	91
World(2)	18	59	76	153
Total	58	127	153	338

(1) without Hungary
(2) without Europe
(3) only the first 9 months in this year

Table 2 shows the distribution of these accidents among three interesting regions.
It is interesting to mention that the rates of the accident types (their severity) in this statistics strongly depend on the region of the accident. An example: a "turn on side" of a minibus without fatalities is reported by the Hungarian media only if it happened in Hungary, but it is not news if it happened in Brasilia or China. This is proved by Table 3. The conclusion of this effect is that the more severe rollover accidents are over-represented in this accident statistics considering the whole world.

Table 3.
The rates of accident types in the regions

Regions	Turned on side	Rollover from the road	Serious roll-over	Comb. roll-over	total
Hungary	45 48%	43 46%	0 0%	6 6%	94 100%
Europe(1)	18 20%	40 44%	13 14%	20 22%	91 100%
World(2)	2 1%	43 28%	59 39%	49 32%	153 100%
Total	65 19%	126 37%	72 21%	75 23%	338 100%

(1) without Hungary (2) without Europe

Remarks to Table 3.

- This statistics is projected by the Hungarian media. It means that the Hungarian figures are almost complete (90-95%), so it may be said that it is a representative sample from Hungary.
- Assuming a proportional figure in Europe, based on the fleet sizes of buses (18.000 in Hungary and 500-550 thousand in Europe) the estimated number of the rollover accidents in Europe could be in the range of 380-480 rollovers/year. If so, the European figures in this statistics cover only 2-4% of the total, which is not representative sample. It may be said that it is a useful, usable signal from Europe.
- The rollovers outside Europe may be used as individual information, but they can be involved into the statistical evaluation of certain questions, special aspects.

Table 4. summarizes the number and the rate of PRA-s in this statistics.

Table 4.
The rate of PRA-s in the regions.

Regions	All rollover accidents	PRA number	PRA %
Hungary	**94**	**88**	**94%**
Europe(1)	**91**	**58**	**64%**
World(2)	**153**	**45**	**29%**
Total	**338**	**191**	**57%**

(1) without Hungary
(2) without Europe

Remarks to Table 4:

- In Hungary the 94% of the rollover accidents belong to PRA (No big mountains, precipices, all rollover accidents are reported even if there was no fatality, no serious injury, etc.) As it was said before, this statistics is representative, related to Hungary
- Related to Europe, this rate is 64% but it is obvious that the Hungarian media do not report the less severe rollover accidents from Europe.
- Considering countries having more and bigger mountains, too, the estimated rate of PRA-s is between these two values, probable closer to the Hungarian one. It seems to be a reasonable estimation that 80-85% - as an European average – of the rollover accidents belong to PRA.
- In other words, if we can provide high level probability of survival and reduce the casualty risk in PRA-s, the passenger protection will be significantly increased in rollover accidents of buses.

THE ROLLOVER PROCESS

It is important to see clearly the rollover process, the factors influencing this process and to understand the problem of severity in case of rollover.

Start of the rollover

The start of the rollover process mechanically is simply and more or less similar in all accidents. A turning moment (*M*) starts the process (see Fig.2.) which may be generated on two ways:

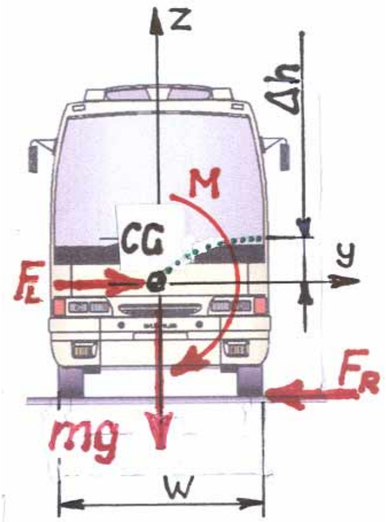


Figure 2. Turning moment and other parameters.

a) If the one side wheels of the bus run into the air, no vertical supporting forces on these wheels, the turning moment *M* is:

$$M = mg\frac{w}{2} \qquad (1)$$

b) If lateral mass force (F_L) – due to a sharp curve or lateral slipping on icy road – is acting in the CG of the bus, lateral friction forces as reacting forces (F_R) are acting on the wheels. The rotations starts around the axis running trough the wheel foot points, if the turning moment is big enough:

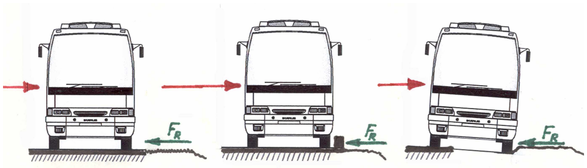
$$M = m\,g\frac{w}{2}\mu \rangle mg\frac{w}{2} - hF_L \qquad (2)$$

and the kinetic energy of the bus is enough to elevate the CG into the unstable position:

$$E_{kin} \rangle mg\Delta h \qquad (3)$$

In these equations
- m is the total mass of the bus
- μ is the friction coefficient
- g is the gravitational constant
- w is the extended track (see Figure 2.)

If there is no friction (μ = 0) there is no turning moment, no rollover, only slipping away. Bigger friction coefficient bigger turning moment. The friction coefficient, more exactly the reaction force (F_R) could be increased by certain circumstances (see Figure 3.)



Metalled wayside *kerb stone on wayside* *soft soil wayside*

Figure 3. Increasing of the reaction (friction) force

The simplest rollover is the "turn on side", with ¼ rotation. This is the end of the first part of the rollover process. This happens on a horizontal (or closely horizontal) ground, see Fig.4. The bus slips on its side, the reaction (friction) force (F_R) is acting on the sidewall. The possible axis of the further rotation A_r is at the cantrail. No further rotation, if the kinetic energy of the bus can not elevate the CG into the unstable position (Δh). The sliding will be stopped by the friction (energy consumption), finally the bus will be laying on its side.

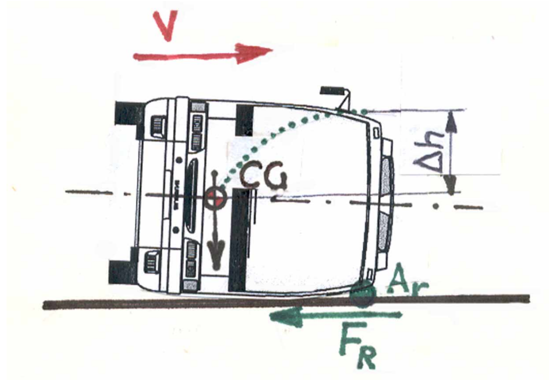


Figure 4. Turn on side.

The further motion in rollover

Studying the further motion of the bus – after turn on side – two essentially different processes may be distinguished:

- Energy consuming process, when the kinetic energy of the bus is decreasing by the energy absorption of the friction work, by the deformation work (structural and/or local) and by the elevation of the CG, etc. This process leads to stopping the further rotation of the bus.
- Energy generating process, when the kinetic energy of the bus is increasing by the drop of the CG (e.g. sliding or rolling down on a slope) If the energy generated by the drop of the CG (ΔE_g) is bigger than the energy absorbed by the friction and deformations (ΔE_a):

$$\Delta E_g \rangle \Delta E_a \qquad (4)$$

the motion of the bus (sliding or rotation) will continue.

The further motion of the bus depends on the surroundings (general geometry of the scene of the accident, soil properties, locality of the ground, etc.) and on the properties of the bus (shape, CG position, stiffness of the superstructure, etc.) Let us consider the two essential influences.

General geometry of the scene

To understand the effect of the general feature of the scene of the rollover, let us presume the same starting position: the bus already turned on its side and is sliding on its side crosswise. Figure 5. shows examples about the possible general geometry of the surroundings. Different surroundings, different further motion of the bus, different severity in the rollover process.

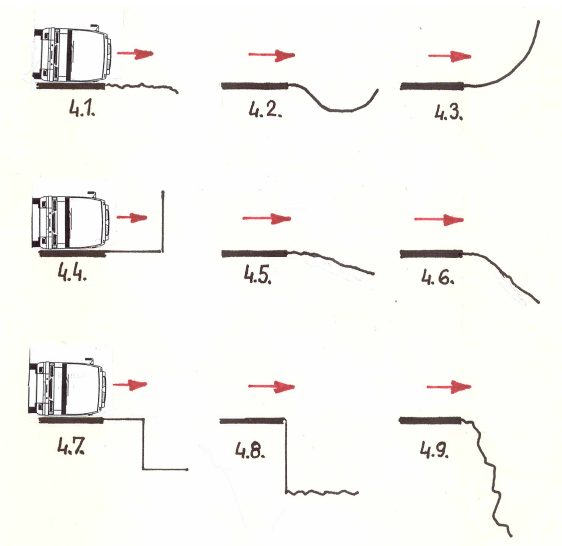


Figure 5. Examples for the general geometry of the surroundings.

Explanation to Figure 5.

4.1. horizontal ground with different surface
4.2. ditch with different shape
4.4. wall like object wayside
4.5 slight slope with different length
4.7. step like level difference
4.8. level difference with water, down
4.9. precipice with different depth

Stiffness of the superstructure.

There are two major aspects. The first is the general stiffness (or strength) of the superstructure having two alternatives: the superstructure is strong enough, no considerable deformation in the standard rollover described in the regulation ECE-R.66, or the superstructure is weak, large scale structural deformation or collapse occurs (see Fig.6/a) The other one is the local stiffness of the cantrail (outside corner between the roof and sidewall) which may influence the further rotation (see Fig.6/b.)

When studying the further motion of the bus in a rollover accident, it has to be recognized that the surroundings and structural stiffness have common effects, too. [3]

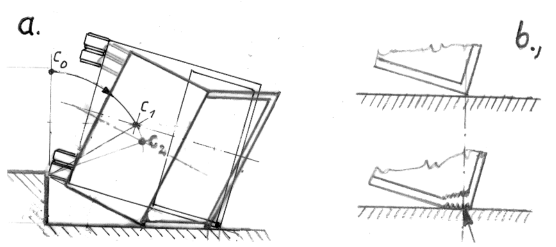


Figure 6. Stiffness of the superstructure

SEVERITY OF ROLLOVER ACCIDENTS

It is interesting and important to specify the severity of bus rollover accidents, at least to specify a "dividing line" between the severe and not severe accidents. It is obvious that the regulatory work should concentrate on the not severe accidents, in which the passengers should be protected, the safety level should be enhanced. There are two different approaches in the common practice when talking about the severity of bus rollovers:

a) Based on the number and severity of casualties. More casualties, more severe accident. The material losses are also considered. The real rollover process does not play role in this approach. A turned into a ditch accident – if the roof collapses and there are many fatalities – is called a severe one in this case.
b) Based on the rollover process. In chapter 3, the list of the different rollover accidents represents an order of the severity, the PRA-s are not severe accidents, but the combined and serious rollovers are severe. This approach does not count the casualties, if an empty bus rolls down on a slope having 20 m level difference and no casualty (because it was empty), the accident is a severe one.

These two approaches sometimes are mixed, and sometimes both approaches specifies an accident as a severe one, or both of them as a non severe one. From the view point of the regulatory work the second approach is more useful, because well defined technical requirements may be derived on the basis of this approach. As it was said earlier, the PRA-s specify those group of the rollovers in which the bus occupants shall be protected, so the dividing live is between PRA-s and the severe rollover accidents (serious and combined rollovers)

It is difficult to check, whether the recently used approval test is adequate to separate the strong superstructure from the weak one, to meet the demand of the public, to assure the required safety for the passengers at least in the PRA-s. A slow feedback can be found from this accident statistics, even if this statistics does not give direct information about the efficiency of the approval of buses regarding ECE-Rg.66. Very few information are available, whether the bus having a rollover accident was approved on the basis of R.66 or not. But indirectly an interesting comparison may be done. As it was defined above, PRA-s cover those accidents in which the passengers should be protected, the survival space (SS) shall be maintained. It has to be underline that the required strength of the superstructure helps to avoid the intrusion type injuries, to reduce drastically this type of fatalities, but it is less effective in the projection and ejection type injuries. Among the 388 rollover accidents there are 191 PRA-s and among these accidents there are 142 in which we have information about the behaviour of the superstructure: 82 accidents did not cause damage in the SS and in 60 accidents the SS was harmed, including the total collapse, too. An interesting comparison is shown in Table 5., in which the casualty rates (casualty per accident, CR) are given for four kinds of rollover accident groups:

– All the 388 accidents giving a very general average
– PRA-s in which the passengers should be protected
– PRA-s in which the SS remained intact (studying the pictures, photos, videos available)
– PRA-s in which the SS damaged, the superstructure collapsed.

Table 5.
Casualty rates in rollover accidents

Considered rollovers	Number of events	Casualty rates (CRi)				
		CR_{Fa}	CR_{Si}	CR_{Li}	CR_{Ns}	CR_{AC}
All rollovers	338	12,0	3,0	2,9	7,7	25,6
PRA-s	191	5,5	2,6	3,7	6,3	18,1
SS intact	82	0,9	1,9	4,3	3,6	10,7
SS damaged	60	13,4	6,7	4,2	10,2	34,5

In Table 5.
CR_{Fa} = fatality rate
CR_{Si} = serious injury rate
CR_{Li} = slight injury rate
CR_{Nc} = rate of not specified injuries
CR_{Ac} = all casualty rate

Remarks to Table 5:

- Dealing with the casualty data in this statistics we have to be careful. The fatalities are acceptable statistically (as reported from the scene) and also the total number of the injuries, but their real severity is questionable. The number of the serious injury is strongly underestimated.
- The fatality rates clearly show the essential importance of the SS. If the survival space is damaged, the fatality rate is higher with one order (15 times) compared to the unharmed SS. The rates of the serious injuries show also a significant difference (3,5 times higher)
- On the basis of these statistical data it may be said that the casualty risk of intrusions can be drastically reduced by the requirement of the intact SS, by the required strength of the superstructure.
- It is interesting to mention - on the basis of Table 5. - that the slight injury rates are not closely related to the kind of rollover groups. It may be assumed that this type of injuries are caused mainly by projection (the inside collision of the passengers) when they are leaving their seats, seating position during the rollover process. The main tool to reduce this kind of injuries could be the use of seat belts. (It has to be emphasized that the seat belt can reduce the number of fatalities and serious injuries, too, and also the ejection of the passengers.)

When starting to work with R.66 (in the mid of '70s) one of the most important and long discussed question was to find on appropriate standard approval rollover test. At that time there was no clear idea about the PRA-s, but there was a demand for a "good" approval test which separates the strong superstructures from the weak ones. Figure 7. shows three kind of rollover tests used in Hungary.

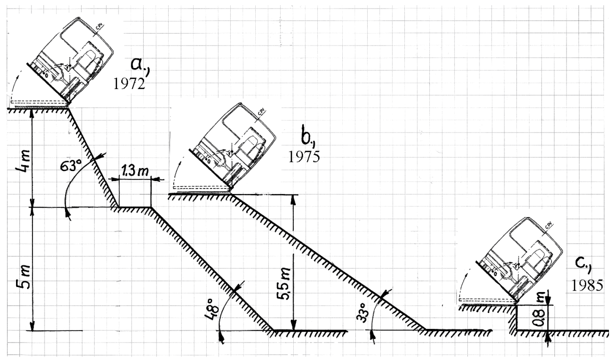


Figure 7. Different rollover tests, used and proposed by Hungary

This test series gave a good possibility to compare their results because the same bus types were used, altogether 8 full scale real rollover tests were carried out [4] The most severe test is – producing the most severe dynamic impact load on the cantrail – the version "c", which, at first glance seems to be the less severe one. Test "b" separated also the weak superstructure (see Figure 8.) from the strong one. Figure 9 shows the same test with the same bus type in which two reinforcing safety rings were installed and the survival space remained intact during the test, the superstructure did not collapse. But the comparison with the test "c" – using the same weak and reinforced buses – showed that the reinforced bus needed some further reinforcement at the rear part of the superstructure (see Figure 10.)

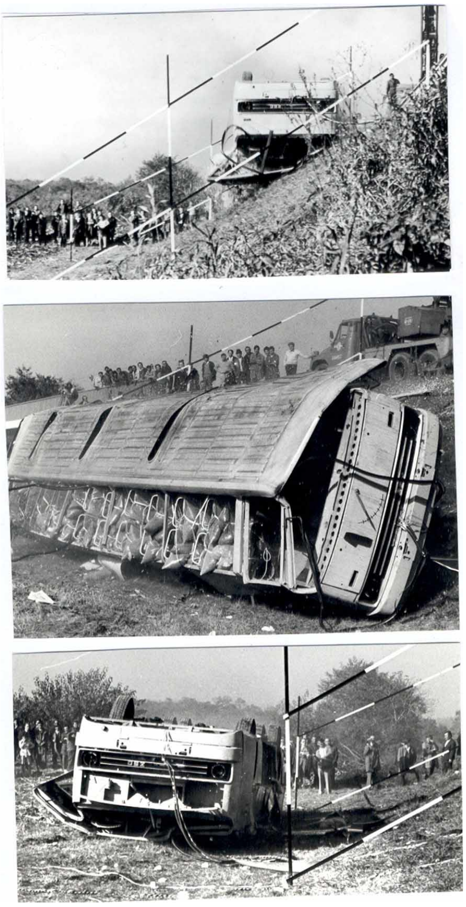


Figure 8. Rollover test with weak superstructure

Figure 9. Rollover test with reinforced superstructure

week superstructure

reinforced superstructure

Figure 10. Comparison with test "c"

Many real rollover accidents proved the effectiveness of the recent approval rollover test described in R.66. which is the same as the version "c" on Figure 7. Some examples are shown on the next figures Figure 11. shows the result of a rollover accident, which happened on a slope very similar to the version "b" on Figure 7. after 1,5 rotation. The level difference was around 6 m, the superstructure was "original", that means without reinforcement. After two steps reinforcement (and approval according to R.66) this reinforced bus had a rollover accident on a slope given in Figure 12. The level difference was around 9-10 m, the number of rotation 2 ¼ and after this accident no significant deformation could be observed on the superstructure. [5] (see Figure 13.)

Figure 11. Result of real rollover accident (Superstructure not reinforced)

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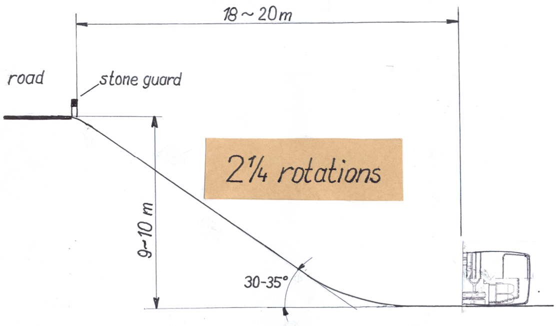

Figure 12. The scene of the rollover accident

Figure 13. After rollover no significant deformations

Another bus type – also approved according to R.66 – may be seen on Figure 14. after a rollover accident slope, number of rotation ¾, the level difference is around 5-6 m. An interesting test was published by Volvo [6] With an approved bus, having the required strength of superstructure a rather severe rollover test was carried out on the slope shown on Figure 15. After 3 ¼ rotations – the level difference was 17-18 m – the survival space remained intact, the intrusions were avoided. Nine dummies were used in this test, 7 of them had 3pts safety belt, 2 of them were without belt. The belted dummies remained in their seats, (no projection type injury) but the two unbelted dummies flew in the passenger compartment and had untraceable motion. According to our definition, this rollover accident is out of the PRA group (more than 2 rotations, more than 10 m level difference) it belongs to the severe rollovers. But having the required strength of superstructure and wearing seat belt, the survival probability of the occupants is strongly increased even in severe rollover accidents, too.

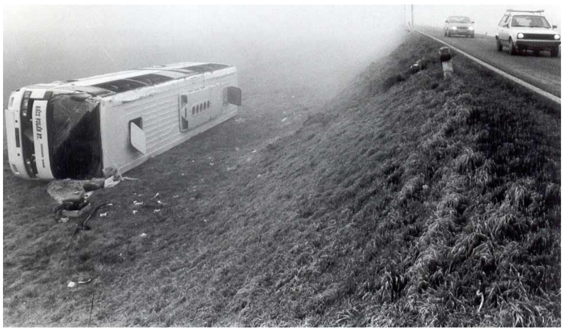

Figure 14. Rollover accident of an approved bus type

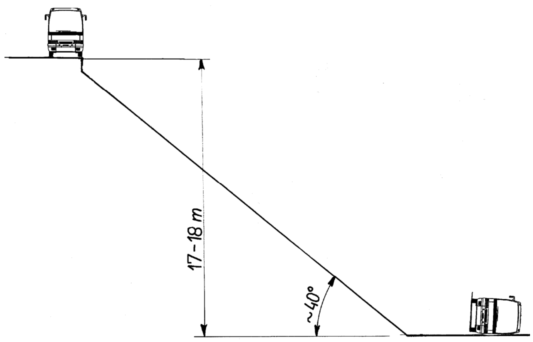

Figure 15. VOLVO's rollover test

TWO EXAMPLES

Thinking about the severity of rollover accidents, it could be interesting to study in details the following two accidents.

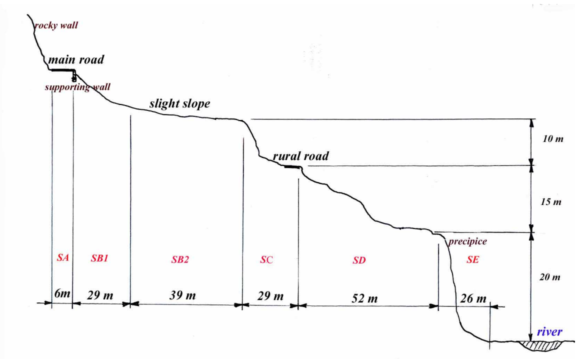

Figure 16. The path of the rollover

Switzerland, Grand St.Bernard Pass, 17.04.2005

HD tourist coach, 27 occupants on board rolled down from a mountain road The result: 12 fatalities, 15 serious injuries, 4 of them were in life danger. The path of the rollover process is shown on Figure16. Next to the road there was a 60-70 m long slight slope on which the bus had 6-7 rotations. After that a steeper section came, finally a 20 m deep rocky precipice completed the path of the bus. The final position and the completely collapsed roof can be seen on Figure17. Asking the question: was it a severe accident? – both approaches give positive answer, yes it was. But a detailed study proved [3] that if the bus should have had a strong superstructure which did not collapse at the first impact, the bus could slip away on the slight slope and stop before the steeper section. Of course certain injuries could happen in this case, too, but perhaps both approaches could say: no, it was not a severe accident.

Figure 17. Final position of the collapsed bus

Hungary, Balatonszentgyörgy, 10.07.2002

The HD tourist coach, 51 occupants on board, run into a roundabout with relatively high speed (The driver did not recognize the situation, it was gloom, night.) After uncontrolled manoeuvre the bus turned on its side, slipped away on the double-way roundabout 20-25 m and hit the other side of a ditch next to the roundabout. (see Figure18.) The roof structure completely collapsed as it may be seen on Figure19. The result: 20 fatalities, 17 serious injuries and 14 slight injuries. [7] The tip over (turned on side) is the less severe rollover based on the 2^{nd} approach. But the first approach says, it is a very severe accident. But if the superstructure should have had the required strength, both approaches could say that this is not a severe accident. The public opinion says: it is unacceptable that in a similar accident (tip over) the casualty rates are so high. And that is the goal of the international regulatory work: to increase the safety, to avoid this kind of results in PRA-s.

Figure 18. The ditch, in which the bus landed

Figure 19. The collapsed roof structure

CONCLUSIONS

- The protectable rollover accidents (PRA) in which the bus occupants shall be protected may be and shall be defined.
- Every individual rollover accident is strongly influenced by the surroundings, the general geometry of the scene, but the process is similar for all bus categories.

- The severity of the rollover should be defined on the rollover process itself and not on the measure (number) of the casualty figures.
- The survival space concept and the belonging existing requirements are very effective. Statistical data prove that the all casualty rate is 3 - 4 times lower, the fatality rate is lower with one order (10 times) when the survival space remains intact in a PRA.
- There are four important injury mechanisms which should be considered enhancing the passenger safety in rollover. The most dangerous one is the intrusion, when due to the large scale structural deformation structural parts intrude into the passenger, or compress them (lack of the strength of superstructure)

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NHTSA RESEARCH EFFORTS TO SIGNIFICANTLY IMPROVE BRAKING PERFORMANCE OF MEDIUM AND HEAVY TRUCKS

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ABSTRACT

In 1999, National Highway Traffic Safety Administration (NHTSA) researchers theorized that substantial improvements could be made in the braking performance of medium and heavy trucks. Therefore, NHTSA initiated a multi-year research program to learn what improvements in stopping performance could be achieved using advanced, but currently available, brake technology for medium and heavy trucks.

Truck tractors were the first type of heavy truck studied. Tractor testing results, including dry stopping distance, wet brake-in-curve stability evaluations, and wet split coefficient of friction stopping distances are presented. Testing results showed that a 30 percent reduction in maximum permissible dry stopping distances is possible for U.S. truck tractors, with no degradation in other performance areas. Objective measurements of brake torque, measured on NHTSA's inertial brake dynamometer at speeds up to 112.7 kph, are presented. Vehicle dynamics simulation results were used to understand effects that higher-torque brakes might have on jackknife stability during braking of tractor-semitrailer rigs.

Changing tractors to have all air disc brakes make braking performance improvements attainable with incremental costs that are outweighed by the expected benefits. Unforeseen improvements include a nominal 5 to 8 percent improvement in stopping distance during ABS-controlled stops on wet pavement, a result of significantly lower brake hysteresis with air disc brakes. Hybrid brake configurations, utilizing larger, more powerful S-cam drum brakes or air disc brakes on the steer axle only, are also shown to provide significant performance improvements over current foundation brakes. Based on this research, NHTSA has proposed revising FMVSS 121; shortening the maximum permitted stopping distance for truck tractors by 20 to 30 percent.

The paper concludes by briefly discussing NHTSA's research to improve the stopping performance of medium and heavy straight trucks.

INTRODUCTION

In the United States, Federal Motor Vehicle Safety Standards (FMVSS) 105 and 121 currently require medium and heavy trucks (vehicles with Gross Vehicle Weight Ratings (GVWR) of 4,537 kg to 11,794 kg are medium trucks, ones with a GVWR of more than 11,794 kg are heavy trucks) to stop from 96.6 kph, on a high coefficient of friction pavement and with properly working brakes, in the distances shown in Table 1. In comparison, FMVSS 135 requires light vehicles (vehicles with a GVWR of 4,536 kg or less except for motorcycles) to stop, in similar conditions, in 70.0 meters from 100.0 kph. These standards also set required failed system/emergency brake stopping distances (not shown). Required failed system/ emergency brake stopping distances are substantially longer for medium and heavy trucks than for light vehicles.

Table 1: Current Stopping Distance Requirements for Medium and Heavy Trucks

Type of Vehicle	Empty Stopping Distance	Loaded Stopping Distance
Bus	85.3 m	85.3 m
Single Unit Truck	102.1 m	94.5 m
Truck Tractor	102.1 m	N/A
Truck Tractor with Unbraked Control Trailer	N/A	108.2 m

In 1999, NHTSA researchers theorized that substantial improvements (approximately 30 percent reductions in stopping distance) could be achieved in the braking performance of medium and heavy trucks through the use of modern air disc or improved S-cam drum brakes. Based on this thinking, NHTSA Research and Development started performing research to improve medium and heavy trucks' stopping performance.

THE SAFETY PROBLEM

On March 10, 1995, NHTSA published three final rules that reestablished stopping distance requirements for medium and heavy trucks (a 1978 court decision had invalidated these requirements due to concerns about the reliability of medium and heavy truck antilock braking systems (ABS)). These rules also improved the directional stability and control of heavy vehicles during braking by mandating ABS on these vehicles. The phase-in period for the requirements of these rules ended on March 1, 1999.

Crash statistics indicate that the number of fatal and injury crashes for medium and heavy trucks built subsequent to this rulemaking has slightly declined even while the number of vehicle miles traveled (VMT) by these vehicles has increased. However, due to the large number of medium and heavy trucks in the United States, the total number of crashes for these vehicles remains high. Based on data contained in [1], during 2002:

- 434,000 medium and heavy trucks were involved in crashes in the United States.
- 4,542 medium and heavy trucks were involved in fatal crashes killing 4,897 people.
- 130,000 people were injured in medium and heavy truck crashes.

According to [2], in 2001 the medium and heavy truck fatality rate (fatalities per 100 million VMT) was 60 percent higher than the comparable rate for light vehicles (those vehicles with a GVWR of 4,536 kg or less).

NHTSA'S STRATEGY

NHTSA decided to initially focus its research (and subsequent rulemaking) efforts on truck tractors (referred to simply as "tractors" throughout the remainder of this paper). The reasons for selecting this type of vehicle to be our focus were:

1. According to [2], in 2001 while the medium and heavy truck fatality rate was 60 percent higher than the comparable rate for light vehicles, the fatality rate for combination vehicles (tractors pulling one or more trailers) was nearly double that of light vehicles. In comparison, the fatality rate for single-unit trucks was 15 to 20 percent higher than the fatality rate for light vehicles.

2. From [3], although medium trucks (GVWR) of 4,537 kg to 11,794 kg) comprised almost 45 percent of truck sales during the years 2000 – 2001, they were involved in just 11 percent of fatal crashes. Heavy trucks, over half of which are tractors, were involved in the other 89 percent of fatal crashes. Combination vehicles were involved in 2,686 fatalities (63 percent of medium and heavy truck fatalities).

3. There are a relatively limited number of kinds of tractors. The most common tractor is the standard-weight three-axle 6x4 with a front gross axle weight rating (GAWR) of 6,623 kg or less and a rear tandem drive axle with a GAWR of 20,412 kg or less. According to the Truck Manufacturers Association (TMA) and Freightliner, this type of tractor comprises 82 percent of United States production. Freightliner stated that two-axle 4x2 tractors comprise ten percent of tractor production, and severe service tractors comprise seven percent (due to rounding, Freightliner's numbers add to 99 percent). TMA described a severe service tractor as having three axles with either a steer axle GAWR greater than 6,623 kg or tandem drive axles with a total GAWR greater than 20,412 kg. In addition, severe service tractors include those tractors with twin steer axles, auxiliary axles (e.g., lift axles), and/or tridem drive axles. Chassis configurations include 6x4, 8x4, 8x6, 10x6 and 14x4 layouts. However, the specialty chassis configurations (anything other than 6x4) comprise only about one percent of all United States tractor production. For research purposes, NHTSA decided to focus on the standard-weight 6x4 tractor and the 4x2 tractor. NHTSA is currently in the process of performing testing using a simulated 6x4 severe-service tractor.

4. In contrast to tractors, there are many common configurations of straight trucks, including large pickup trucks, flat-bed trucks, trash trucks, dump trucks, and concrete mixers. Much more effort is required to research these many configurations than is the case for tractors.

5. While there are only a limited number of common trailer configurations, NHTSA researchers theorized that most of the improvement in vehicle stopping performance would come from increasing the torque output of the front brakes of a vehicle. Therefore, much more limited safety benefits will be achieved by improving trailer brakes.

While NHTSA is obviously interested in also improving the stopping performance of medium and heavy straight trucks, the research necessary to perform rulemaking for this type of vehicle was delayed until after the tractor research was completed. Straight truck research is currently in progress and will briefly be described at the end of this paper. Research to improve trailer brakes may be performed after the completion of the straight truck research.

Trailer brake stopping distance improvement research has not yet begun and will not be discussed further in this paper.

METHODOLOGY FOR NHTSA DRY TRUCK TRACTOR STOPPING DISTANCE RESEARCH

Research was initiated at NHTSA's Vehicle Research and Test Center (VRTC) in 2001 to evaluate possible improvements in tractor braking performance.

NHTSA researchers, based partially on discussions with air brake suppliers, theorized that most of the improvement in tractor stopping performance would come from increasing the torque output of the front brakes of the tractor. Based on information received and NHTSA's testing experience, NHTSA researchers thought that tractor front axles typically were "underbraked," i.e., their brakes could not produce enough torque to lock up the wheels on the front axle during a full treadle brake application on a high coefficient of friction pavement. There was also thinking that air disc brakes, on all axles, would improve stopping performance due to improved fade resistance and greater torque production consistency.

Based upon this, NHTSA decided to study tractors with four foundation brake configurations: standard S-cam drum brakes plus three "advanced" configurations. The foundation brake configurations examined were:

1. Standard S-cam drum brakes on all axles. These were the brake configurations received with the two 6x4 tractors tested when they were purchased from their manufacturers. This brake configuration will be referred to as "standard drum" throughout the remainder of this paper.

2. Larger S-cam drum brakes on the steer axle and standard S-cam drum brakes on the rear axles. Larger (hence higher torque output), but still commercially available, S-cam drum brakes were fitted onto the steer axle. This was the brake configuration received with the 4x2 tractor tested when it was purchased. This brake configuration was expected to be a relatively inexpensive method of improving tractor braking. However, it was not clear prior to performing this research how much improvement in stopping performance would be gained from this brake configuration versus the improvement that could be gained with the more expensive brake configurations listed below. This brake configuration will be referred to as "hybrid drum" throughout the remainder of this paper.

3. Air disc brakes on the steer axle and standard S-cam drum brakes on the rear axles. Commercially available air disc brakes were fitted onto the steer axle. Air disc brakes typically have substantially greater torque output than do standard steer-axle S-cam drum brakes. This brake configuration was expected to cost more than the hybrid drum configuration but less than the all air disc configuration (described below). This brake configuration will be referred to as "hybrid disc" throughout the remainder of this paper.

4. Air disc brakes on all axles. This brake configuration was expected to be the most expensive bake configuration tested. This brake configuration will be referred to as "all disc" throughout the remainder of this paper

All brake configurations, other than those received when the vehicles were purchased from their manufacturers, were field retrofitted onto the vehicles at VRTC. All of the parts used during these retrofits were commercially available. While the brakes on the retrofitted vehicles worked well, they may not have been as optimized to work with each vehicle's ABS system as were each vehicle's original brakes. Therefore, the braking improvements seen in VRTC's testing are believed to be conservative; manufacturers could do better by optimizing a vehicle's original equipment brakes.

Additional information about the brakes used for each foundation brake configuration is contained in [4] and [5].

Three tractors were tested. All three tractors were fitted with original equipment ABS. Two of these were standard-weight 6x4 tractors: a 1991 Volvo 6x4 tractor and a 1996 Peterbilt 6x4 tractor, both of which had 5,443 kg gross axle weight rating (GAWR) steer axles, 17,237 kg GAWR tandem drive axles, and of 22,680 kg GVWRs. The third tractor was a 2000 Sterling 4x2 tractor with a 5,443 kg GAWR front axle, a 10,297 kg GAWR rear axle, and a 15,740 kg GVWR.

The Sterling 4x2 tractor was originally tested with its as received wheelbase (3.759 m). However, in response to industry concerns that a shorter wheelbase 4x2 tractor might have more stability problems, VRTC has shortened the wheelbase of this tractor to 3.454 m. At the time this paper was written, VRTC was in the process of retesting this tractor. Limited preliminary results are included in this paper.

Tractors were tested at two loadings: LLVW and GVWR. LLVW consisted of a “bobtail” tractor (i.e., one not towing a trailer) that was empty except for a test driver and instrumentation. In the GVWR loading, the tractor was towing an unbraked control trailer of the type used for FMVSS 121 tests. This single axle trailer was loaded so as to achieve the tractor GVWR plus 2,041 kg on the trailer axle.

The following information about the testing methodology is taken from [4]. Additional details may be found in that report.

Full-treadle braking stops were conducted for each tractor at both loadings for each brake configuration. The experienced professional test driver was instructed to fully apply the brakes within 0.2 seconds after the initiation of braking. Full-treadle brake applications were used to obtain the shortest possible stops and to maximize repeatability; each vehicle’s ABS modulated the brake line pressure at each wheel so as to prevent wheel lockup from occurring. Stopping distance testing was performed in accordance with the FMVSS 121 test procedure.

Testing was performed on the Transportation Research Center, Inc.’s dry concrete skid pad. This pad has nominal peak and slide coefficients of friction of 98 and 84, respectively.

Brake pad temperatures were monitored as outlined in the FMVSS 121 test procedure. Initial brake pad and/or lining temperatures were in the range of 65.5 to 93.3° C prior to the initiation of each stop.

Stopping distances were measured with a fifth wheel assembly mounted on the tractor frame. Stopping distances were recorded using a Labeco Tracktest Fifth Wheel System Performance Monitor, which displays both the speed at which the brakes were first applied and the vehicle’s stopping distance. All measured stopping distances were corrected as per the standard method prescribed in SAE J299 to the intended initial speed of 96.6 kph. Six consecutive repetitions were performed for each tractor-loading-brake configuration tested.

Both average and minimum stopping distances were computed from the six stops. While this paper focuses on the minimum stopping distances (since these are what is used in FMVSS 121 compliance testing), average stopping distance results are contained in [4]. The spread of stopping distances during the six stops was generally small. The difference between the average and the minimum stopping distance was typically three to four percent.

RESULTS FROM NHTSA DRY TRUCK TRACTOR STOPPING DISTANCE RESEARCH

Some of the stopping distances presented in the tables below are taken from [4]. The remainder are new data collected by VRTC.

Tables 2 through 5 summarize the bobtail stopping distances for each of the tractors tested for each foundation brake configuration. Each of these tables includes a column titled Margin of Compliance which contains the percentage by which the measured stopping distance is less than the mandated maximum of 102.1 m.

Table 2: Measured LLVW Stopping Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	61.9	39.4
Hybrid Drum	61.0	40.3
Hybrid Disc	53.9	47.2
All Disc	55.2	46.0

Table 3: Measured LLVW Stopping Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	67.7	33.7
Hybrid Drum	58.2	43.0
Hybrid Disc	53.9	47.2
All Disc	53.6	47.5

Table 4: Measured LLVW Stopping Performance for 2000 Sterling 4x2 Tractor (3.759 wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	58.2	43.0
Hybrid Disc	54.6	46.6
All Disc	55.8	45.4

Tables 6 through 9 summarize the stopping distances for each of the tractors tested loaded to GVWR (by towing an unbraked control trailer) for each foundation brake configuration. Again, each of these tables includes a margin of compliance column. This shows the percent margin of compliance versus the 108.2 m maximum permitted by FMVSS 121.

Table 5: Measured LLVW Stopping Performance for 2000 Sterling 4x2 Tractor (3.454 m wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	57.9	43.3
Hybrid Disc	52.7	48.4
All Disc	Not Yet Tested	N/A

Table 6: Measured GVWR Stopping Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	79.2	26.8
Hybrid Drum	80.4	25.6
Hybrid Disc	75.9	29.9
All Disc	71.6	33.8

Table 7: Measured GVWR Stopping Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	93.6	13.5
Hybrid Drum	76.2	27.0
Hybrid Disc	71.3	34.1
All Disc	66.4	38.6

Table 8: Measured GVWR Stopping Performance for 2000 Sterling 4x2 Tractor (3.759 wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	73.5[1]	32.1
Hybrid Disc	68.0	37.2
All Disc	61.0	43.7

Table 9: Measured GVWR Stopping Performance for 2000 Sterling 4x2 Tractor (3.454 m wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	87.8	18.9
Hybrid Disc	71.0	34.4
All Disc	Not Yet Tested	N/A

For tractors tested loaded to GVWR (by towing a loaded, unbraked control trailer), the situation is not as good as it was for the LLVW tractors. While all vehicles easily met the FMVSS 121 requirement, compliance margins exceeding 30 percent were generally achieved only for foundation brake configurations that included air disc brakes on at least the tractor's steer axle.

Data from NHTSA's dry pavement testing confirmed NHTSA researchers' theory that improvements in tractor stopping performance could be achieved by increasing the torque output of the front brakes of the tractor. This trend is clearly present in the data presented in Tables 2 through 9.

All foundation brake configurations tested have some margin of compliance versus the current FMVSS 121 standards. To determine whether a 30 percent reduction in maximum permitted stopping distances is feasible with the advanced brake configurations, the test results in Tables 2 through 9 are compared to the reduced stopping distance (i.e., a 30 percent reduction from either 102.1 m (71.5 m) or 108.2 m. (75.7 m)). For example, the hybrid disc configuration in Table 7 would show a 5.8 percent margin of compliance for the reduced stopping distance. Likewise, the all disc configuration would have a 12.3 percent margin of compliance. Although the margins of compliance are lower with the reduced stopping distances, both tractors and loadings tested had at least one advanced brake configuration that stopped shorter than the reduced stopping distance. The test results show that a 30 percent reduction in the maximum permitted stopping distances in FMVSS 121 is feasible.

Additionally, at GVWR for all tractors for which data are currently available, an improvement in stopping performance was seen from the hybrid disc case to the all disc case. For these two brake configurations, the front brake torque is being generated by the same brake hardware. Even though the front brake torques for these two cases are the same, the margin of compliance for the all disc configuration averaged 5.0

[1] The stopping distance achieved with original equipment brake linings was not repeatable with replacement linings. With replacement brake linings, a minimum stopping distance of 101.2 m was achieved for the hybrid drum configuration. This was the only condition for which different stopping performance was found with replacement linings.

percent higher than for the hybrid disc case. This effect is believed to be due to the improved fade resistance of the all disc configuration since no improvement was seen for the LLVW case. (Brake fade should be less of a problem at lighter loadings.)

METHODOLOGY FOR NHTSA WET TRUCK TRACTOR BRAKE RESEARCH

Brake in a wet, slippery curve stability testing and straight-line stopping on a wet, split-coefficient of friction surface testing (split-mu testing for short) were performed for both the 1996 Peterbilt and the 1991 Volvo 6x4 tractors. Additional information about this testing can be found in [6].

Brake-in-curve stability testing was performed to check for any possible degradation in vehicle lateral stability during braking due to one of the advanced foundation brake configurations. This testing was performed on a wetted Jennite surface on the Transportation Research Center, Inc.'s Vehicle Dynamics Area. The test surface was wetted within one minute of the commencement of each braking run. A single 3.7 m wide lane was marked with pylons on a 152.4 m radius curve. The measured peak coefficient of friction of this curve varied between 0.30 and 0.46 during this testing. (The slide coefficient of friction was not monitored.) This varying peak coefficient of friction caused the FMVSS 121 brake-in-curve passing speed to change from vehicle to vehicle and from brake configuration to brake configuration.

The brake-in-curve stability test protocol began by performing the procedures contained in S5.3.6 of FMVSS 121 and in Section 10.3-D of the FMVSS 121 Laboratory Test Procedure [7]. Following completion of the FMVSS 121 brake-in-curve stability procedure, testing was continued to find the maximum initial (i.e., curve entry) speed at which the professional test driver (with more than 10 years experience) could keep the vehicle within the 3.7 m lane while braking in the curve. To determine the maximum initial speed, the initial speed was increased by 1.6 kph increments above the terminal speed that was determined during the FMVSS 121 brake-in-curve stability testing, up to the speed at which the vehicle consistently slid out of the lane.

NHTSA researchers hypothesized that vehicles with air disc brakes will stop in a shorter distance in a split-mu situation. Split-mu testing was performed to test this hypothesis. This testing was also performed on the Transportation Research Center, Inc.'s Vehicle Dynamics Area. The test course consists of one half lane of wetted asphalt and one half lane of wetted Jennite. The measured peak/slide coefficients of friction of the wetted asphalt averaged 0.86/0.60 while for the wetted Jennite they averaged 0.35/0.10 during this testing.

For test efficiency, a stop from an initial speed of 48.2 kph was made in one direction (east-to-west), then a stop in the opposite direction (west-to-east). Six stops were performed at each test condition, three in each direction. Again, both average and minimum stopping distances were computed from the six stops. While this paper focuses on the minimum stopping distances (since these are what is used in FMVSS 121 compliance testing), average stopping distance results are contained in [6].

The test driver was instructed to establish 48.2 kph while approaching the wetted test course in a straight-ahead approach. Upon reaching a traffic pylon (positioned such that the entire vehicle would be on the wetted surface at the instant braking began), the driver would apply full treadle braking within 0.2 seconds. The professional test driver would apply corrective steering during the stop to keep the vehicle inside the 3.7 m lane.

Stopping distance data collection and correction were performed in the same manner as was discussed for the dry stopping distance research.

RESULTS FROM NHTSA WET TRUCK TRACTOR BRAKE RESEARCH

Tables 10 through 13, which contain data from [6], summarize the results of the FMVSS 121 portion of the brake-in-curve testing. As the tables show, both tractors passed the FMVSS 121 brake-in-curve requirement for all foundation brake configurations. However, the hybrid drum and hybrid disc configurations seem to be performing slightly worse, only passing three out of four tests (the FMVSS 121 required minimum number of passes) in the LLVW Peterbilt test.

Table 10: LLVW Brake-in-Curve FMVSS 121 Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	37.0	4
Hybrid Drum	38.7	4
Hybrid Disc	40.3	3
All Disc	41.9	4

Table 11: LLVW Brake-in-Curve FMVSS 121 Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	40.3	4
Hybrid Drum	45.1	3
Hybrid Disc	43.5	3
All Disc	40.3	4

Table 12: GVWR Brake-in-Curve FMVSS 121 Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	37.0	4
Hybrid Drum	37.0	4
Hybrid Disc	40.3	3
All Disc	41.9	4

Table 13: GVWR Brake-in-Curve FMVSS 121 Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	40.3	4
Hybrid Drum	41.9	4
Hybrid Disc	46.7	3
All Disc	40.3	4

As was mentioned above, following completion of the FMVSS 121 brake-in-curve stability procedure, testing was continued to find the maximum initial speed at which the test driver could maintain the vehicle within the 3.7 m lane while braking in the curve. The limit vehicle initial speed was used to calculate its "Lateral Acceleration Performance Quotient" (LAPQ). LAPQ is defined as the ratio of the maximum attainable lateral acceleration (calculated from curve radius and initial speed) during the brake-in-curve test divided by the maximum drive-through lateral acceleration (with no braking) expressed as a percentage. Rationalizing vehicle/brake configuration performances in this way normalizes the limit brake-in-curve speed as a function of the limit drive-through speed. Since both tests were performed on the same day, the variability of the pavement's coefficient of friction is largely mitigated.

Tables 14 through 17, which contain data from [6], summarize the results of the LAPQ portion of the brake-in-curve testing.

Table 14: LLVW Brake-in-Curve LAPQ Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	49.9	40.3	65
Hybrid Drum	51.5	41.9	66
Hybrid Disc	53.1	49.9	57
All Disc	54.7	40.3	83

Table 15: LLVW Brake-in-Curve LAPQ Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	53.1	54.7	103
Hybrid Drum	59.6	54.7	92
Hybrid Disc	58.0	49.9	74
All Disc	53.1	53.1	100

Table 16: GVWR Brake-in-Curve LAPQ Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	48.3	45.1	87
Hybrid Drum	49.9	38.6	60
Hybrid Disc	53.1	45.1	72
All Disc	54.7	54.7	100

Table 17: GVWR Brake-in-Curve LAPQ Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	53.1	54.7	106
Hybrid Drum	56.4	56.4	100
Hybrid Disc	62.8	51.6	67
All Disc	53.1	46.7	77

Just as with the number of passes of FMVSS 121 brake-in-curve requirement, for LAPQ the hybrid drum and hybrid disc configurations seem to be performing slightly worse than the standard drum and all disc configurations. NHTSA researchers speculate that this may be because the hybrid brake configurations are not as optimally tuned as the standard drum or all disc configurations. Additional research would be required to prove or disprove this conjecture.

Stopping distance results from the split-mu testing were analyzed combining results from both tractors. This was done so as to give a more representative comparison of foundation brake effects for the real world in which there is a large and varied fleet of 6x4 tractors having different layouts in terms of suspension design, wheelbase, ABS controls, etc.

Tables 18 and 19, which contain data from [6], summarize the results of the split-mu testing with data from the two tractors combined together.

Table 18: LLVW Split-Mu Performance with Data From the Two Tractors Combined

Foundation Brake Configuration	**Mean Stopping Distance** (m)	**Standard Deviation** (m)
Standard Drum	32.1	1.5
Hybrid Drum	32.5	3.9
Hybrid Disc	31.6	1.1
All Disc	29.3	1.1

Table 19: GVWR Split-Mu Performance with Data From the Two Tractors Combined

Foundation Brake Configuration	**Mean Stopping Distance** (m)	**Standard Deviation** (m)
Standard Drum	30.1	2.0
Hybrid Drum	30.8	1.7
Hybrid Disc	30.8	0.6
All Disc	28.3	0.8

Examination of Tables 18 and 19 leads to two interesting points. First, the mean stopping distance at both the LLVW and GVWR loadings is shortest for the all disc foundation brake configuration. All brake configurations, for any load condition up to and including GVWR, were capable of locking the wheels on any axle while on the split-mu course (this is not the case for the dry pavement testing). Therefore, the apparent advantage in stopping ability on the split-mu course for the all disc foundation brake configuration is attributed to efficiencies in their operation beyond their ultimate capacity to generate brake torque.

Second, the GVWR stopping distance variability (as indicated by the standard deviation of stopping distance) was lower for the configurations that include air disc brakes. This indicates that the air disc brakes have a more consistent torque output than do drum brakes. Improved consistency of torque output (versus drum brakes) is seen for hydraulic disc brakes; it appears that this characteristic also carries over to air disc brakes.

These two topics are further discussed at the end of the section of this paper that presents brake dynamometer testing and results.

The split-mu data were analyzed on a tractor-by-tractor basis. However, due to space limitations, a summary of this analysis is not included in this paper. The interested reader is referred to [6].

BRAKE DYNAMOMETER TESTING AND RESULTS

In support of NHTSA's studies of heavy truck brake types and their effects on vehicle stopping performance and stability, NHTSA VRTC evaluated four brakes on its Greening Brake Dynamometer. Results from this study are more fully documented in [8]; only a summary is given here.

Two S-cam drum brakes and two air disc brakes were tested. The two S-cam drum brakes were the two S-cam drum brakes that were on the rear axles of the 1991 Volvo and 1996 Peterbilt when they were tested in their standard drum configuration. Similarly, the two air disc brakes tested were the two rear axle air disc brakes from these vehicles when tested in their all disc configuration. One disc and one drum brake were from Manufacturer A; the other disc and drum brake were from Manufacturer B. To allow data to be treated statistically, five copies of each brake were tested.

The brakes were tested on VRTC's Greening Brake Dynamometer. The dynamometer was set up to simulate the conditions seen by the rear axles of the Volvo and Peterbilt during the testing described earlier in this paper. Testing consisted of five parts: brake burnish, retardation testing, fade and recovery testing, additional retardation testing, and dynamic input testing. The brake burnish, retardation testing, and fade and recovery testing were performed in accordance with the FMVSS 121 dynamometer test procedures described in [9].

Following completion of the FMVSS 121 testing, additional retardation testing was performed. Additional retardation tests with 620 and 690 kPa brake applications at 80.5 kph were performed. The brake retardation procedure was then repeated for speeds of 48.3, 96.6, and 112.7 kph, at treadle application pressures from 138 to 690 kPa.

After completion of additional brake retardation testing, some brake assemblies were subjected to low frequency dynamic pressure inputs designed to evaluate the brake assembly's transient response characteristics. The input pressure dynamics were intended to compare how different brakes might perform under the control of ABS or Electronic Stability Control systems. The dynamic input stops were performed from speeds of 48.3, 80.5, and 96.6 kph. The following five dynamic inputs were used:

1. Sinusoidal input,
2. Triangular wave input,
3. Swept sinusoidal input,
4. Step input, and
5. Series of step inputs.

A complete description of these inputs is in [9].

Sample results from the brake dynamometer testing are shown below. Again, more complete results are contained in [9]. Figure 1 summarizes the brake retardation test results for Manufacturer A's S-cam drum brake. Each data point represents the mean of data from five brakes tested at speeds of 48.3, 80.5, 96.6, and 112.7 kph for a range of brake application pressures. Third order polynomial fit lines indicating the 95 percent confidence intervals about the mean torque outputs bound the data series for each speed. As can be seen from Figure 1, there is a 50 percent reduction in the S-cam drum brake's output torque for an application pressure of 690 kPa as the speed in increased from 48.3 to 112.7 kph.

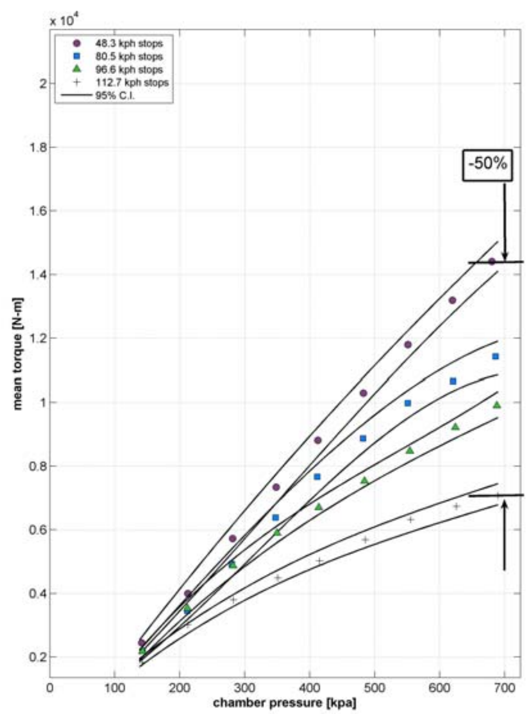

Figure 1: S-cam drum brake torque spreads – Manufacturer A.

Figure 2 summarizes the brake retardation test results for Manufacturer A's air disc brake. The format of this figure is exactly the same as Figure 1's; only the brake tested has changed. As can be seen from Figure 2, there is a 21 percent reduction in the air disc brake's output torque for an application pressure of 690 kPa as the speed is increased from 48.3 to 112.7 kph.

Similar figures are available for Manufacturer B's brakes. Due to space limitations, these figures are not included in this paper. However, they show the same trends as Figures 1 and 2. Table 20 summarizes the reduction in torque output for all four brakes tested torque for an application pressure of 690 kPa as the speed is increased from 48.3 to 112.7 kph.

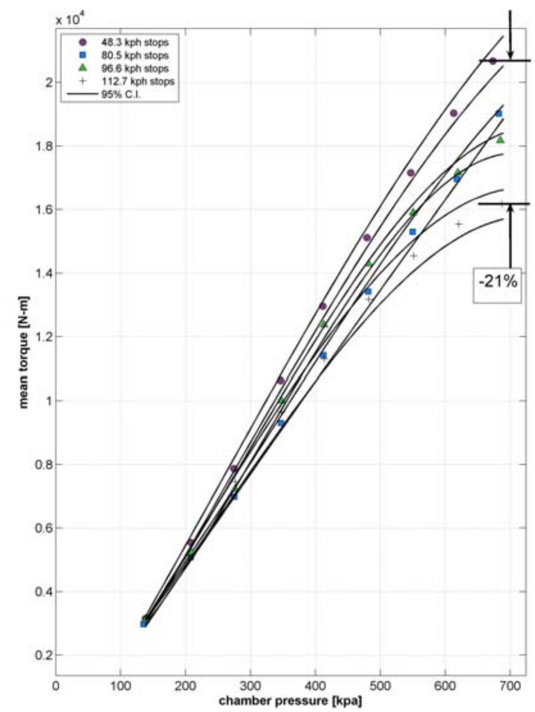

Figure 2: Air disc brake torque spreads – Manufacturer A.

Table 20: Nominal Percent Loss in Maximum Brake Torque as Speed is Increased from 48.3 to 112.7 kph.

Brake Type	Manufacturer A	Manufacturer B
S-cam Drum	-50 %	-42 %
Air Disc	-21 %	-24 %

The air disc brakes retained much more of their low-speed performance potential at high speeds than did their S-cam brake counterparts. However, the low-to-medium speed performance of the S-cam brakes could be on par with the air disc assemblies, given the appropriate combination of brake chamber size, slack adjuster length, and lining and drum materials. The performance differences at higher vehicle braking speeds are directly attributable to thermal and mechanical disadvantages that affect S-cam drum brakes' performance at high speed and energy levels.

One set of results from the dynamic pressure input testing is shown in Figure 3. This figure is for Manufacturer A's S-cam drum and air disc brakes. The particular dynamic pressure input used to generate Figure 3 is a sinusoidal input with a period of 2.5 seconds. Normalized (current brake torque divided by maximum brake torque expressed as a percentage) hysteresis plots are shown. The upper panel shows data from Manufacturer A's S-cam drum brake while the lower panel shows data from Manufacturer A's air disc brake.

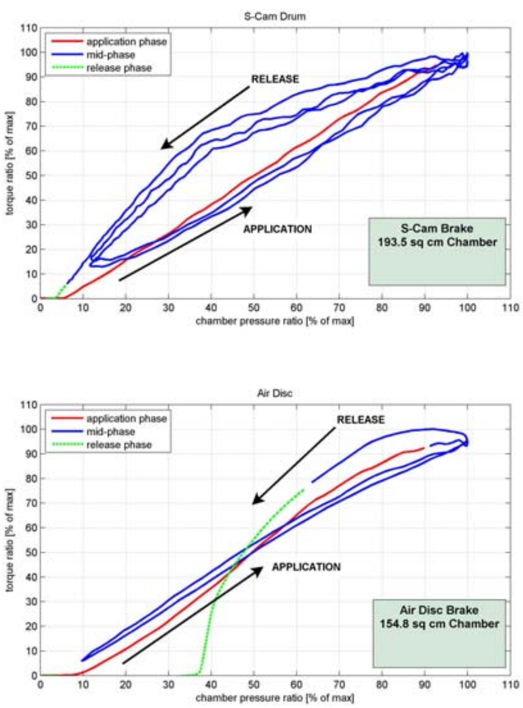

Figure 3: Sinusoidal wave input (2.5-second period) from 96.6 kph on S-cam drum (type 30 chamber) and air disc (type 24 chamber) brakes by Manufacturer "A" – normalized torque versus pressure.

Figure 3 shows that the air disc brake had less hysteresis than the corresponding A's S-cam drum brake. Similar results were seen for the other brake for the other smoothly varying dynamic pressure inputs.

Another set of results from the dynamic pressure input testing is shown in Figure 4. This figure shows hysteresis for an abruptly changing pressure input (a step with a very fast rise time). As Figure 4 shows, there was a substantial increase in air disc brake hysteresis, to approximately the levels seen for S-cam drum brakes, for the suddenly changing step inputs.

The reduction in hysteresis for smoothly varying dynamic pressure inputs is believed to be, at least partially, responsible for the advantage in stopping ability on the split-mu course for the all disc foundation brake configuration that was pointed out earlier in this paper. It is also thought to contribute to the reduction in stopping distance variability on a split-mu surface that is seen for configurations that include air disc brakes.

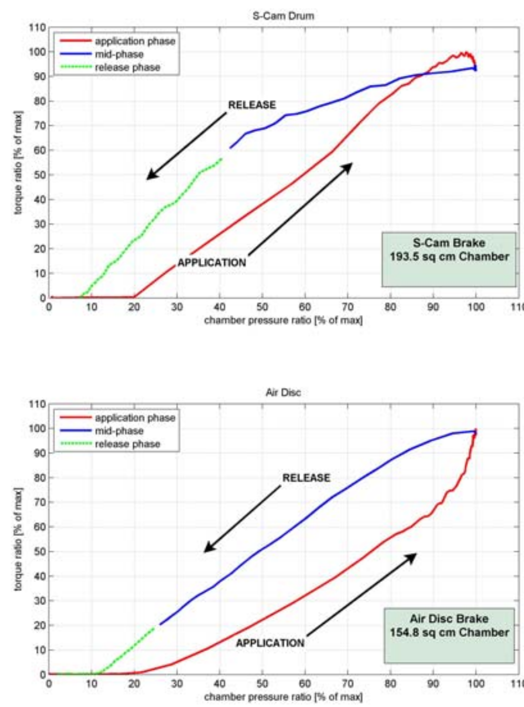

Figure 4: Step input and release from 96.6 kph on S-cam (type 30 chamber) and air disc (type 24 chamber) of Manufacturer "A" – normalized torque versus pressure.

On the split-mu course, the coefficient of friction between the vehicles' tires and the pavement limited stopping distance, not the magnitude of the torques generated by the vehicles' brakes. In other words, the vehicles' brakes had sufficient capacity to lock up the vehicles' tires; the brakes could do no more to stop the vehicle. To prevent wheels from locking up, the vehicles' ABS was cycling during the stop. The cycling of the ABS generates smoothly varying dynamic pressure inputs of the type for which S-cam drum brakes exhibit higher hysteresis than do air disc brakes. This higher hysteresis increases the percent of time for which the torque output of S-cam drum brakes is reduced due to the cycling of the ABS. This in turn, increases the vehicles' stopping distances. It also increases the variability in vehicles' stopping distances by making the torque produced by a brake for a given application pressure depend more upon the time history of the air pressure at the brake chamber.

SIMULATION STUDY OF EFFECTS OF SHORTER TRUCK TRACTOR STOPPING DISTANCES ON JACKKNIFE STABILITY

One concern with improving the braking performance of tractors is that this requires more force to be transmitted from the tractor to the semitrailer during braking. This increased force is transmitted through the articulation point formed by placing the fifth wheel/kingpin into compression. If the vehicle is not traveling straight ahead, a component of the force acting through the wheel/kingpin articulation point acts to push the rear tandem axle (assuming a 6x4 tractor; nothing really changes for a 4x2 tractor except that "rear tandem axle" would be replaced by "rear axle") sideways. If the rear axle(s) is pushed too hard sideways, its limit of adhesion might be exceeded. When this occurs, the rear axle(s) move rapidly sideways and a "jackknife" occurs. (A jackknife is defined as an event in which the tractor rotates rapidly in yaw until it strikes the semitrailer.)

Due to the relatively small changes in the forces involved, this is a difficult topic to study by means of test track testing. Therefore, NHTSA researchers decided to perform a simulation study to examine whether the theoretical mechanism just described will, in fact, occur for actual tractors. Additional details about this research, beyond those that will fit into this paper, are contained in [10].

The heavy truck dynamics simulation package used for this research was TruckSim™ version 5.0 [11]. The TruckSim software is a commercially available, multi-body dynamics simulation package intended for use in simulating medium and heavy trucks. It treats the vehicle chassis, suspension, and drivetrain masses as a collection of rigid bodies. Linear and nonlinear forces and moments both act on the vehicle and are applied internally to hold the vehicle together. The TruckSim software simulates the dynamics of the vehicle, including highly nonlinear aspects such as tire force models, suspension deflection models, leaf spring models, and the hitch model.

The tractor simulated during this research was the same 1991 Volvo 6x4 that has been used for much of the testing described in this paper. For this simulation research, the Volvo tractor was towing a 16.0 m long 1992 Fruehauf van trailer. The geometric, inertial, steering, suspension and tire properties of this tractor-semitrailer are documented in [12] and [13]. The validation of this model is documented in [14].

One attractive feature of TruckSim is that advanced vehicle component models, written using Simulink, can be used to model portions of the vehicle that are of particular interest for a research program in far greater detail than they are normally modeled by TruckSim. For this research, an advanced brake system model was developed. A nonlinear Simulink model was written that provided a detailed model of the Volvo tractor/Fruehauf trailer's brake system dynamics, brake torque outputs, and brake hysteresis. This model is described in greater detail in [10] and [15].

The detailed brake system model developed for this research includes the following significant features:

- First-order differential equations model system dynamics for the control (treadle) circuit and main brake actuation circuits.
- Time delays for control (treadle) signals are based on the physical location of the associated modulator valve.
- Four-sensor/four-modulator (4s/4m) integrated ABS control system for the tractor.
- Two-sensor/two-modulator (2s/2m) integrated ABS control system for the semitrailer.
- Simulated ABS controller calculations lag.
- ABS control strategy based on longitudinal wheel slip level and tangential acceleration, tuned to match actual vehicle performance on wet and dry surfaces.
- Quadratic model of brake torque output as a function of application speed and chamber pressure.
- Brake system hysteresis as seen in modern S-cam drum brakes.
- The ability to simulate air disc brakes with various sizes of pneumatic brake chambers using data generated by VRTC's Greening Brake Dynamometer.

The simulation study examined the performance of the Volvo tractor towing the Fruehauf semitrailer.

The Volvo tractor was equipped with either S-cam drum brakes or air disc brakes. The Fruehauf semi-trailer was always equipped with S-cam drum brakes.

Two vehicle loadings were simulated: no payload, and with the semitrailer loaded with five concrete blocks (two in the front of the semitrailer, three in the rear), each with a mass of 1,928 kg. This loaded the combination vehicle to one-half of GVWR. GVWR loading was not simulated because preliminary analyses indicated that, for the situations being studied, jackknifing was more likely to occur with a less loaded vehicle.

These preliminary analyses also indicated that, for the situations being studied, jackknifing was more likely to occur on a low coefficient of friction roadway. Therefore, the two road surfaces simulated both had lower coefficients of friction than would a dry road. One had a peak coefficient of friction (mu-peak) of 0.55 (corresponding to wet Jennite) and the second had a mu-peak of 0.30 (corresponding to snow with some ice covered pavement). Realistic traction surfaces were simulated by having the levels of adhesion vary slightly around their above listed means. Variance of the surface coefficient of friction about its mean was deemed necessary to simulate "real-world" surfaces, which do not have constant coefficients of friction.

The maneuver simulated was brake-in-curve, similar to the previously described experimental wet testing. The same 152.4 m curve radius was used. The curve entry speed (initial speed) was dependent upon the vehicle loading and the pavement coefficient of friction. The initial speed was set so as to attain 90 percent of the lateral acceleration seen during the highest lateral acceleration, successful, simulated drive-through of the 152.4 m radius curve.

Two brake applications were simulated: Full Treadle and Half Treadle. For a Full Treadle brake application, air pressure at the treadle valve was ramped from 0 to 690 kPa in 0.3 seconds. For a Half Treadle brake application, air pressure was ramped from 0 to 345 kPa in 0.5 seconds. Two ABS configurations were examined: fully operational and non-operational.

Tables 21 and 22 summarize the results from the simulated jackknife stability study. The number in each cell of these tables is the maximum tractor yaw rates, in degrees per second. Each cell's background color indicates the jackknife stability for that particular condition with white indicating that there was no stability problem, light gray indicating a near jackknife (high hitch articulation angle and/or high hitch forces), and dark gray indicating that a jackknife occurred.

Examination of Tables 21 and 22 shows the following:

- The peak tractor yaw rate was generally less for the cases with air disc brakes on the Volvo tractor than for cases with S-cam drum brakes.
- No simulated jackknifes or near jackknifes were seen for the ABS On case.

Table 21: Simulated Jackknife Stability Results - Vehicle with no load

		0.55 Mu-Peak		**0.30 Mu-Peak**	
		Drum	**Disc**	**Drum**	**Disc**
Half Treadle Brake Apply	**ABS On**	6.9	6.2	5.8	5.6
	ABS Off	49.7	19.3	4.7	2.2
Full Treadle Brake Apply	**ABS on**	6.4	6.6	6.0	6.2
	ABS Off	8.8	3.5	2.0	1.2

Table 22: Simulated Jackknife Stability Results - Vehicle loaded to one-half GVWR

		0.55 Mu-Peak		**0.30 Mu-Peak**	
		Drum	**Disc**	**Drum**	**Disc**
Half Treadle Brake Apply	**ABS On**	7.2	6.7	7.5	6.7
	ABS Off	50.9	34.9	7.8	2.6
Full Treadle Brake Apply	**ABS on**	6.9	6.4	7.5	7.6
	ABS Off	12.5	6.0	2.3	1.3

- Multiple simulated jackknifes and near jackknifes were seen for the ABS Off case. However, either jackknifes/near jackknifes were seen for both the S-cam drum brakes and the air disc brakes or they were seen for just the S-cam drum brakes. No cases were found for which there was a jackknife/near jackknife for air disc brakes for which S-cam drum brakes did not also have a problem.

In summary, NHTSA's simulation study of jackknife stability for combination vehicles found that, whether ABS was functional or not, the higher torque output brakes on the tractor displayed no negative effects on jackknife stability for the brake-in-curve maneuvers simulated.

COSTS AND BENEFITS OF SHORTER TRUCK TRACTOR STOPPING DISTANCES

NHTSA has estimated the costs and benefits of improving tractor-stopping distances. Only a brief summary is given here; additional information about these topics can be found in [3] and [16].

First, NHTSA estimated the target population for this research. The target population consists of braked heavy truck crashes in which the front of the truck hits another vehicle or object. NHTSA used 2000 through 2002 FARS data to estimate the average annual number of fatalities and 2000 through 2002 GES data to estimate the annual number of property damage only (PDO) vehicle involvements and injuries in the United States. Table 23 summarizes these estimates.

Table 23: Estimated Number of Involvements in Braked Heavy Truck Crashes

Crash Type	Injury Level	Number
PDO	**None**	**39,628**
Injury	**AIS 1**	**11,837**
Injury	**AIS 2**	**1,718**
Injury	**AIS 3**	**668**
Injury	**AIS 4**	**95**
Injury	**AIS 5**	**51**
Fatal	**Fatal**	**978**

As explained in detail in the Preliminary Regulatory Impact Analysis, Notice of Proposed Rulemaking – FMVSS No. 121, Air Brake Systems, Stopping Distance, NHTSA estimated safety benefits for both 20 percent and 30 percent reductions in maximum permitted tractor stopping distance. A 20 percent reduction in maximum permitted tractor stopping distance is estimated to prevent 104 fatalities per year in the United States, reduce 120 serious (AIS 3 through 5) injuries per year, and save between $32 million (3 % discount rate) and $27 million (7 % discount rate) in property damage. A 30 percent reduction in maximum permitted tractor stopping distance is estimated to prevent 257 fatalities per year in the United States, reduce 284 serious (AIS 3 through 5) injuries per year, and save between $166 million (3 percent discount rate) and $136 million (7 percent discount rate) in property damage. (The discount rates account for the fact that these savings will occur at some time in the future. Therefore, their present value must be discounted. NHTSA uses both a 3 percent and a 7 percent discount rate for all present value calculations.)

Potential compliance costs for the 20 percent and 30 percent reductions in maximum permitted tractor stopping distance vary considerably and are dependent upon the type of brake systems chosen by the vehicle manufacturers and purchasers. Although the research suggests that air disc brakes at all wheel positions would be most effective in reducing stopping distance, NHTSA's data also indicates that either larger (higher torque output) S-cam drum brakes on just the steer axle or air disc brakes on just the steer axle could also achieve these stopping distance reductions. NHTSA's cost estimates do not include potential costs for changes to the vehicle frame or suspension, possible increased fuel costs, or maintenance costs. With these caveats, NHTSA estimates that the cost to comply with a 30 percent reduction in maximum permitted tractor stopping distance would vary between $153 per vehicle for larger S-cam drum brakes on just the steer axle to $1,308 per vehicle for air disc brakes on all axles. The cost for air disc brakes on just the steer axle is estimated at $536 per vehicle. The costs of achieving a 20 percent reduction in tractor stopping distance would be approximately one-third lower.

Table 24 summarizes the estimated costs for the entire United States vehicle fleet of these brake improvements.

Table 24: Estimated Annual Costs for Upgrading the Entire United States Tractor Fleet

	Larger Drum Brakes on Steer Axle	**Air Disc Brakes on Steer Axle**	**Air Disc Brakes on All Axles**
20 % Reduction	$14 Million	$50 Million	$119 Million
30 % Reduction	$20 Million	$70 Million	$170 Million

To determine the net costs, the estimated annual property damage savings were subtracted from the estimated annual costs for the entire fleet. To determine the equivalent lives saved, NHTSA used a weighting formula for the AIS 1 through AIS 5 injuries and added this number to the estimated fatalities prevented. Using this information, the net cost per equivalent life saved was calculated as summarized in Tables 25 and 26.

Table 25: Net Cost per Equivalent Life Saved for a 20 Percent Reduction in Tractor Stopping Distance

Brake System	3 Percent Discount	7 Percent Discount
Larger Drum Brakes on Steer Axle	Property damage savings exceeds costs	Property damage savings exceeds costs
Air Disc Brakes on Steer Axle	$156,000	$251,000
Air Disc Brakes on All Axles	$743,000	$968,000

Table 26: Net Cost per Equivalent Life Saved for a 30 Percent Reduction in Tractor Stopping Distance

Brake System	3 Percent Discount	7 Percent Discount
Larger Drum Brakes on Steer Axle	Property damage savings exceeds costs	Property damage savings exceeds costs
Air Disc Brakes on Steer Axle	Property damage savings exceeds costs	Property damage savings exceeds costs
Air Disc Brakes on All Axles	$13,000	$144,000

NHTSA MEDIUM AND HEAVY STRAIGHT TRUCK STOPPING DISTANCE RESEARCH

Although a few wrap-up work items remain to be performed, NHTSA has nearly completed its research aimed at improving the stopping performance of tractors. The next focus will likely be improving the stopping performance of medium and heavy straight trucks. A very brief summary of NHTSA research performed to date for these vehicles will be given.

A considerable amount of NHTSA research has already been performed on the stopping performance of existing medium and heavy straight trucks ([17] and [18], plus another upcoming report). These studies evaluated the braking performance of vehicles with their original equipment brakes.

NHTSA has also completed one heavy straight truck study (documented in [19]) in which two vehicles, a Class 7 school bus and a Class 8 straight truck, were fitted with standard S-cam drum brakes, hybrid disc brakes, and all disc brakes, just as was done for the tractor studies described earlier in this paper. This study performed, among other testing, straight line stopping on a dry, high coefficient of friction pavement. For the Class 7 school bus, relative to the standard drum foundation brake configuration, 9.9 percent and 22.0 percent nominal reductions in stopping distance, respectively, were found for the hybrid disc and all disc configurations. For the class 8 straight truck, the nominal improvements were 10.4 percent and 20.0 percent, respectively.

NHTSA is continuing its research to improve medium and heavy straight truck stopping performance. There are, of course, many medium and heavy straight truck configurations sold which makes this a much more difficult problem than was the case for tractors. One strategy that NHTSA is using is that the braking performance of eight heavy straight trucks (with their original equipment brakes) has been measured. The straight truck with the poorest braking performance of these eight is in the process of being tested in the hybrid disc and all disc foundation brake configurations.

CONCLUSIONS

This research has shown that a substantial improvement in tractor stopping performance is possible through the use of modern air disc or improved S-cam drum brakes. No lateral stability or jackknife stability problems were found due to higher torque output brakes on the tractor. A 20 to 30 percent reduction in maximum permitted tractor stopping distance using either air disc or improved S-cam drum brakes has been found to be cost effective.

Based on this research, NHTSA issued on December 15, 2005 a Notice of Proposed Rulemaking [3] that proposed revising FMVSS 121. NHTSA proposed to shorten the maximum permitted stopping distance for truck tractors by 20 to 30 percent.

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STUDY OF HEAVY TRUCK AIR DISC BRAKE EFFECTIVENESS ON THE NATIONAL ADVANCED DRIVING SIMULATOR

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ABSTRACT

In crashes between heavy trucks and light vehicles, most of the fatalities are the occupants of the light vehicle. A reduction in heavy truck stopping distance should lead to a reduction in the number of crashes, the severity of crashes, and consequently the numbers of fatalities and injuries.

This study makes use of the National Advanced Driving Simulator (NADS). NADS is a full immersion driving simulator used to study driver behavior as well as driver-vehicle reactions and responses. The vehicle dynamics model of the existing heavy truck on NADS has been modified with the creation of two additional brake models. The first is a modified S-cam (larger drums and shoes) and the second is an air-actuated disc brake system. A sample of 108 CDL-licensed drivers was split evenly among the simulations using each of the three braking systems. The drivers were presented with four different emergency stopping situations. The effectiveness of each braking system was evaluated by first noting if a collision was avoided and if not the speed of the truck at the time of collision was recorded.

The results of this study show that the drivers who used the air disc brakes will have fewer collisions in the emergency scenarios than those drivers using standard S-cam brakes or those using the enhanced S-cam brakes. The fundamental hypothesis that this research validates can be phrased in this question: "Does reducing heavy truck stopping distance decrease the number and severity of crashes in situations requiring emergency braking?"

INTRODUCTION

According to the Federal Motor Carrier Safety Administration [1], there were approximately 436,000 police reported crashes that involved heavy trucks; 4,289 of them resulted in fatalities. Of these crashes, 298,312 were recorded "Collision with a Vehicle in Transport" as the first harmful event and these resulted in a majority of the fatalities (3,312). The implication of these data is that most of the fatalities involving heavy truck crashes are the occupants of the light vehicles involved.

The National Highway Traffic Safety Administration (NHTSA) believes that reducing the FMVSS 121 (49 CFR Part 571) minimum stopping distance by thirty percent will result in saving a significant number of lives. In generating benefit analyses for estimating the safety effects of improved truck brakes, assumptions have to be made. It has been assumed that if a tractor-trailer can stop in a shorter distance, than fewer crashes will result. Based on kinematics, it is reasonable to assume if you can stop in a shorter distance it is more probable that a truck will avoid colliding with an object or it will at least collide with a reduced velocity. This theory holds true given that the operators' reaction times, control behavior, and their perceptions of available stopping distance remain constant.

Commercial truck drivers understand the braking ability of tractor-trailers and under most conditions drive accordingly. However, in the real world, truck drivers are faced with many adverse conditions in numerous scenarios brought about by other vehicles (light vehicles cutting in-lane, vehicles pulling out unexpectedly, etc.). When a crash-imminent situation occurs, the truck driver must decide to brake, brake and steer, steer, accelerate, or accelerate and steer. Depending on the control behavior adopted by the driver, it can be argued that shorter stopping distance may have little or no effect on avoiding a collision or reducing the delta speed of a crash.

The primary objective of this study is to provide test data that demonstrates the effectiveness of air disc brakes on heavy trucks. This test addresses whether shorter stopping distances reduce the number and severity of certain types of heavy truck crashes. The result will help NHTSA confirm or refine their benefit estimates based on improved truck braking performance.

APPROACH

The effectiveness of air disc brakes on heavy trucks is examined using three different brake system conditions and four simulator scenarios. The three different brake configurations are:

- Standard truck where S-cam brakes are used on all wheels
- Enhanced truck where only the steer axle is equipped with a higher capacity version of an S-cam brake
- Disc truck where all the wheels of the tractor are equipped with disc brakes.

The simulator scenarios are primarily based on those used in previous NHTSA Electronic Stability Control (ESC) research [2]. All simulated roads are built with a shoulder whose traction, vibration, and audio characteristics are different than the on-road pavement. This is to realistically simulate the environment that occurs when some of a vehicle's tires depart the roadway. The lanes are 12 feet (3.7 m) wide, there is 1.9 feet (0.58 m) of road between the white line (designating the outboard edge of the lane) and the shoulder, and the shoulder is 11.5 feet (3.51 m) wide. Beyond the shoulder, there is an additional 75 feet (23 m) of drivable terrain (see Figure 1). The scenarios take place on dry pavement. The virtual environment reflects conditions consistent with pavement. In particular, the scene is clear and the pavement appears dry.

The study used the NADS heavy truck cab and dynamics model [3, 4]. A typical 18-wheel tractor-trailer combination was selected with a gross weight of 73,100 pounds (33,200 kg). Three brake systems were modeled: standard S-cam, enhanced S-cam, and disc brake. Stopping distance is reduced by 17% and 30% when the standard S-cam brake system is replaced by the enhanced and disc systems respectively.

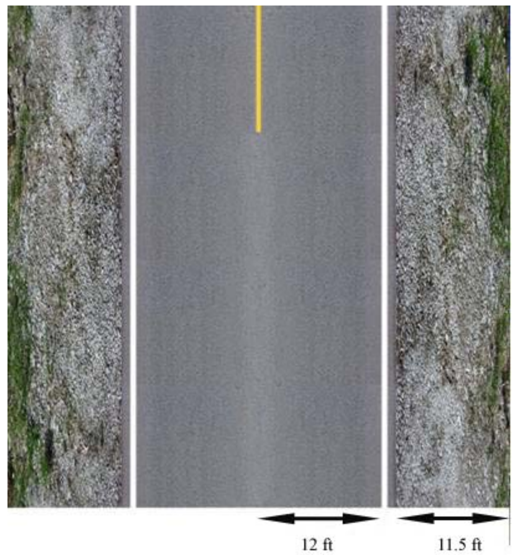

Figure 1. Road geometry.

Truck drivers were recruited from local Iowa trucking companies as well as through radio and newspapers ads targeted at all truck drivers in the area. Participants consisted of drivers who held a valid Commercial Driver's License (CDL) and were between the ages of 22 and 55 (current statistics show that approximately 75% of all drivers involved in heavy truck crashes are between the ages of 22 and 55 and drove on average 2000 miles during the last 3 months). This ensured that participants were actively driving heavy trucks. Since the population of commercial vehicle drivers is comprised of mostly males, no attempt was made to balance by gender. Participant pay in this experiment was comparable with a professional truck driver's hourly wage of $30 per hour plus incentive pay.

A repeated measures experiment design in which participants experienced multiple scenarios was used. Independent variables included brake system (3 levels: standard S-cam, enhanced S-cam, and air disc brakes) and event order (4 events were used, but only 3 events were fully randomized, giving 6 levels; 4th event was always last). A single age group was used (22-55). This design resulted in 18 experimental cells. To allow 6 repetitions of each event order per brake condition, 108 participants who would successfully complete all 4 events were needed. This recruiting goal was met. The principal measure for this study was whether the driver crashed or not. Secondary measures consisted of collision speed (or delta velocity), stopping distance, reaction time to event start, and average deceleration. Other behaviors were tabulated such as if the driver braked, steered, and/or accelerated.

SCENARIO DESIGN

To understand the effectiveness of heavy truck air disc brakes, scenarios were designed to emulate real world situations where heavy truck crashes are occurring. Dry asphalt pavement conditions were simulated. A total of four scenarios containing situations conducive to emergency braking were used. Events are presented to each participant as individual drives. Each participant drove all of the scenarios. Each scenario was approximately five minutes in length and ended immediately after presentation of a conflict event. The scenarios were designed to have consistent entry speed (maintained through monetary incentives) for all participants and no downshifting during the event itself. They were also designed such that the driver can stop without hitting the target vehicle, if the brakes are applied immediately. The scenarios conflict events were:

Right Incursion: The goal of this event is to force the driver to apply brakes to avoid colliding with oncoming traffic. A vehicle pulling out of a hidden driveway attached to a roadside farmhouse combined with carefully timed oncoming traffic creates the conditions for such a maneuver (Figure 2). The driver is approaching a driveway that can hide a vehicle. The driver is motivated via monetary incentives to maintain the speed limit of 55 mph (89 kph). Parked vehicles on the left shoulder prevent the driver from avoiding the oncoming traffic by going left. When the driver is 4 seconds from arriving at the driveway location, the hidden parked vehicle pulls out from the right and stops, blocking the right lane. Drivers who cannot stop within the available distance can collide with white incursion vehicle, green oncoming car, gray oncoming car, or parked truck on left shoulder.

Left Incursion: The goal of this event is to force the driver to react to an incursion from the left and to brake suddenly while traveling at highway speed. The driver is on a two-lane rural highway crossing a heavily wooded area with frequent oncoming traffic (Figure 3). The posted speed limit is 55 mph (89 kph) and the driver is motivated via monetary incentives to maintain speed. There are several parked vehicles on both shoulders. As the driver approaches the location of the event, one of the oncoming vehicles is tasked to arrive at the event location at a fixed relative position to the driver. Oncoming traffic is approaching a parked vehicle on the shoulder opposite to the driver's side. That parked vehicle begins moving and cuts off the oncoming traffic which is forced to veer into the driver's lane. The oncoming traffic will enter driver's lane at a fixed time-distance, 8 seconds away from the driver. Concrete barriers are placed on the right side so that the driver will not steer to the shoulder. If the driver cannot stop within the available distance, the driver can collide with the oncoming red SUV, the black compact, or the concrete barriers.

Stopping Vehicle: The goal of this event is to force the driver to react to an abruptly stopping lead vehicle while traveling at 55 mph (89 kph). There is a continuous flow of oncoming traffic throughout the event and there are barricades and construction vehicles parked along the sides of the road. These barricades and parked vehicles constrain the driver from steering off-road during the braking event (Figure 4). The driver is on a two-lane rural highway crossing a heavily wooded area with frequent oncoming traffic. The posted speed limit is 55 mph. There are several parked vehicles on both shoulders. As the driver is moving along, one of the parked vehicles enters the roadway behind the truck. As the driver cruises along, the following vehicle makes a lane change and overtakes the truck. It enters the driver's lane and maintains a distance of 132 ft (40 m) for approximately 2100 ft (640 m) before it decelerates at the rate of 0.75 g to a complete stop. The driver is precluded from steering via construction barriers on the edge of driver's lane and oncoming traffic in the adjacent lane. Collision can happen with the stopping green lead vehicle, oncoming traffic, or the concrete barriers.

Stopped Vehicle: The goal of this event is to force the driver to react to an obscured stopped vehicle on the highway. The driver is on a 4-lane rural highway traveling at the posted speed limit of 70 mph (110 kph) (Figure 5). There is a steady stream of traffic in the adjacent lane as well in the oncoming lanes. Once the driver achieves the posted speed limit, a delivery truck speeds past him, makes a right lane change into the driver's lane, and becomes the lead vehicle as well as the obscuring vehicle. The lead vehicle maintains a distance of 400 ft (122 m) in front of the driver. When the participant is 610 ft (186 m) from a stopped vehicle, the lead vehicle makes a lane change into a stream of traffic in the adjacent lane revealing the stopped vehicle. The driver can collide with the stopped vehicle or the adjacent oncoming traffic.

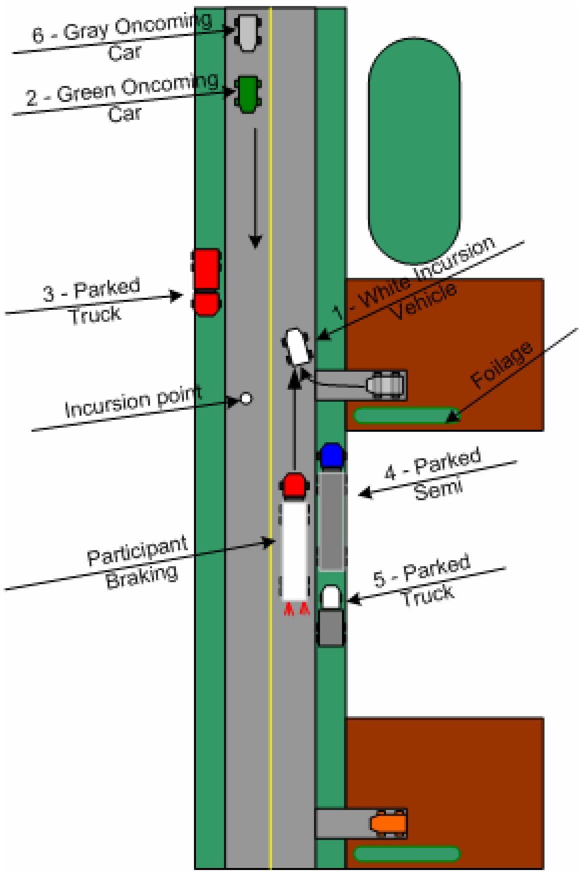

Figure 2. Right incursion.

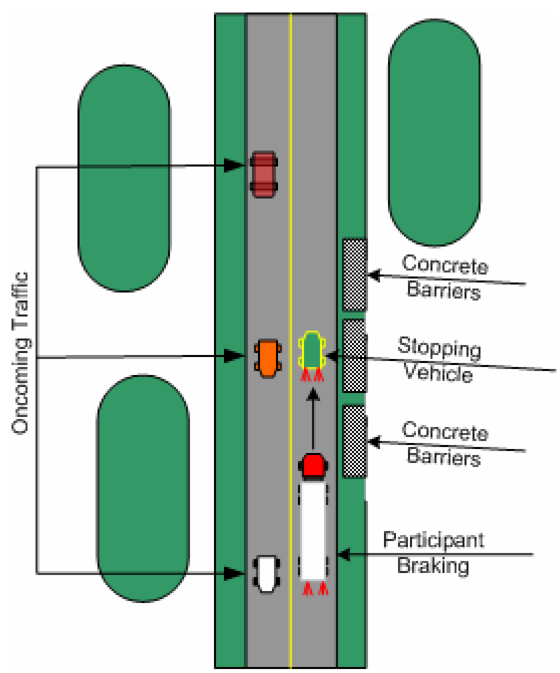

Figure 4. Stopping vehicle.

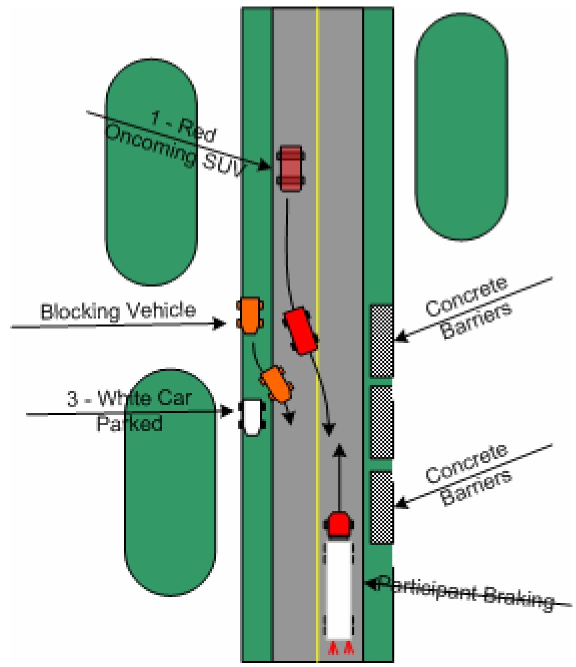

Figure 3. Left incursion.

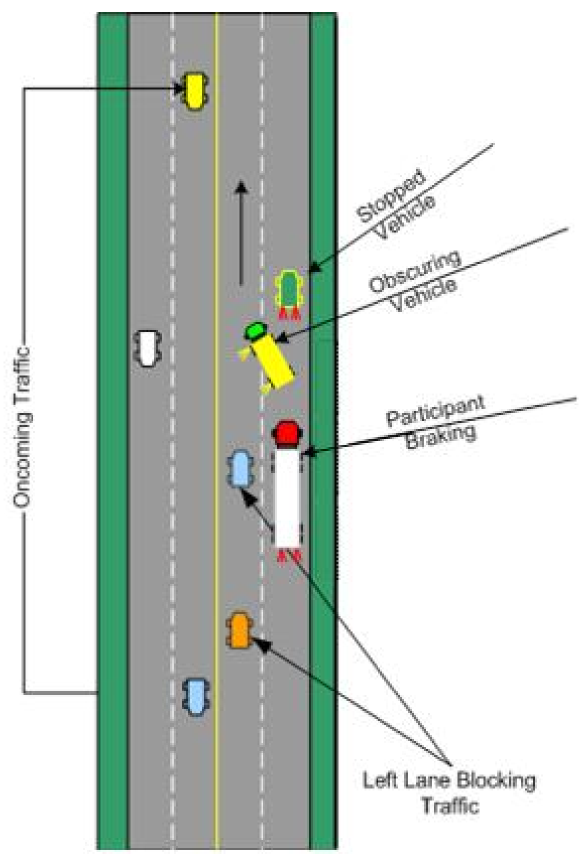

Figure 5. Stopped vehicle.

APPARATUS

The experiment was performed at the NADS facility, located at the University of Iowa's Oakdale Research Park in Coralville. The simulator hardware is described below. Modifications were required to be made to the vehicle dynamics software; in particular to the braking subsystem.

Simulator

NADS consists of a large dome in which an entire vehicle cab (e.g., cars, trucks, and buses) can be mounted. The dome is mounted on a 6-degree-of-freedom hexapod, which is mounted on a motion system, providing 65 feet (20 meters) of both lateral and longitudinal travel. There is a yaw degree of freedom between the hexapod and the dome, which allows 330 degrees of yaw rotation. The NADS motion system has a total of nine degrees of freedom as shown in Figure 6. To simulate high frequency road disturbances and high frequency loads through the tires and suspension, NADS contains four vibration actuators, mounted at points of suspension-chassis interaction. These vibration actuators are mounted between the floor of the dome and vehicle, and they act only in the bounce direction of the chassis. The vehicle cabs are equipped electronically and mechanically using instrumentation specific to their makes and models (Figure 7). The driver is immersed in sight, sound and movement so real that impending crash scenarios can be convincingly presented with no danger to the driver (Figure 8). The NADS capabilities were evaluated by independent simulation experts [5], and the truck system was evaluated by professional drivers [6]. This independent professional assessment of the system provides confidence on the level of realism that can be concluded from the simulator research results.

The Visual System provides the driver with a realistic 360º field-of-view, including the rearview mirror images. The driving scene is three-dimensional, photo-realistic, and correlated with other sensory stimuli. The image generator is capable of rendering 10,740,736 pixels at a frequency of 60 Hz. The Visual System database includes representations of highway traffic control devices (signs, signals, and delineation), three-dimensional objects that vehicles encounter (potholes, concrete joints, pillars, etc.), common intersection types (including railroad crossings, overpasses, bridge structures, tunnels, etc.), and various weather conditions. In addition, high density, multiple lane traffic can be made to interact with the driver's vehicle.

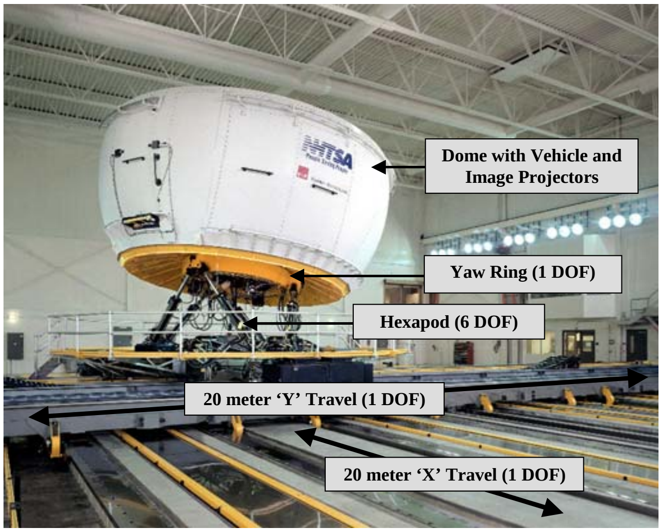

Figure 6. National Advanced Driving Simulator.

Figure 7. Freightliner cab interior.

Figure 8. Truck cab in the NADS dome.

The visual display timing is real time where the driver input and the visual display has less then 50 milliseconds of time delay. This eliminates driver overshoot reactions and possible instability as a result of time delay within a closed-loop-environment. An advanced compensator was developed and installed into NADS to keep the visuals and drivers input in phase [7]. The compensator is similar in capabilities to what is used by NASA at their simulator research facilities [8]. The heavy truck visuals are different from those of passenger vehicles due to the inclusion of the trailer visual display. The truck driver is able to see the trailer from the driver's side mirror, which accurately reflects the rear view of the truck. This is made possible by adjusting the rear image channel to compensate for the curvature of the dome and the offset placement of the mirror. This capability is unique to the NADS due to its 360º horizontal field of view capacity.

The Control Feel System (CFS) for steering, brakes, clutch, transmissions, and throttle realistically controls reactions in response to driver inputs, vehicle motions, and road/tire interactions over the vehicle maneuvering and operating ranges. The CFS is capable of representing automatic and manual control characteristics such as power steering, existing and experimental drivetrains, antilock brake systems (ABS), and cruise control. The control feel cuing feedback has high bandwidth and no discernible delay or distortion associated with driver control actions or vehicle dynamics.

The Motion System provides a combination of translational and angular motion that duplicates scaled vehicle motion kinematics and dynamics with nine degrees of freedom. The Motion System is coordinated with the CFS to provide the driver with realistic motion and haptic cuing during normal driving and pre-crash scenarios. The motion system is configured and sized to correctly represent the specific forces and angular rates associated with vehicle motions for the full range of driving maneuvers. The washout algorithm that is used to generate dynamic specific forces (acceleration at the drivers head with gravity effect) and cab orientation rates is tuned using high sensitivity cuing with a washout scaling of forty-five percent.

In addition, four actuators located at each wheel of the vehicle, provide vertical vibrations that simulate the feel of a real road (Figure 9). NHTSA's Vehicle Research and Test Center (VRTC) measured cab vibrations of a GM-Volvo tractor owned by NHTSA. The vibrations were measured at different engine speeds. Four accelerometers with a maximum capacity of ±4 g were mounted vertically on the truck floor, dashboard, driver seat (actually beneath the seat), and steering handwheel. These measurements provided information regarding the location of the fundamental frequencies and the level of magnitude associated with the vibration feel inside the cab. Harmonic functions that closely replicate the frequencies and magnitude levels (vibration energy) were derived and used to drive the vertical actuators. This method allowed the vertical vibrations to be reproduced with great fidelity inside the cab. The frequency content of these vibrations extended higher than the bandwidth of the hexapod and dome longitudinal and lateral motions. The intensity of these modes at different speeds were measured at VRTC, and in NADS the vibration cues that best represented the speed of the scenarios have been implemented. Figure 10 shows the power spectrum of the truck cab vibration felt at the NADS dome. The 2-Hz frequency is related to truck bounce mode, the 5-8 Hz frequencies are related to axles mode, 10-12 Hz frequencies are related to cab modes, and the 17-25 Hz frequencies are related to engine and power train modes.

Figure 9. Truck cab showing vertical actuator for vibration cues.

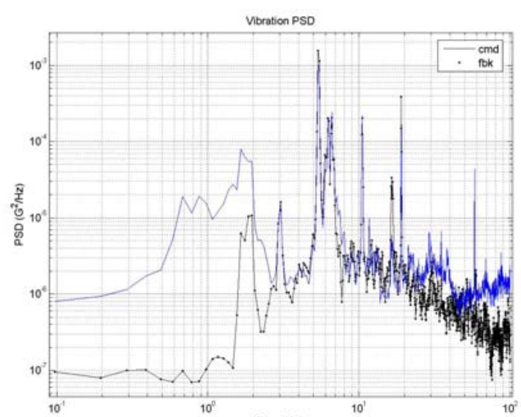

Figure 10. Vibration power spectrum measured on the NADS cab (commanded and measured).

A manual transmission with low and high gear range selection is being used for this study (Figure 11). Before drivers were engaged in the scenarios, they were given ample time (about 20 minutes) to drive and get familiar with the transmission system. Drivers expressed different skill levels; however, none of the scenarios involved in this study required transmission shifting during the braking event.

Figure 11. Truck cab shifting.

The cab steering system was calibrated and the controls were tuned to provide a close steering feel for both on-center and turning maneuvers. VRTC measurements provided the torque-steer curve and the amount of freeplay currently existing in the GM-Volvo truck.

The NADS truck cab system is equipped with a pneumatic brake hardware system. VRTC measured actual brake feel from the GM-Volvo truck and calibrated the NADS cab to reflect accurate brake pedal feel.

The Auditory System provides motion-correlated, three dimensional, realistic sound sources, that are coordinated with the full ranges of the other sensory systems' databases. The Auditory System also generates vibrations to simulate vehicle-roadway interaction. The auditory database includes sounds emanating from current and newly designed highway surfaces, from contact with three-dimensional objects that vehicles encounter (potholes, concrete-tar joints, pillars, etc.), from other traffic, and from the vehicle during operation, as well as sounds that reflect roadway changes due to changing weather conditions. VRTC measured the engine sound of the GM-Volvo truck at different engine RPM and provided the data to NADS to be displayed in real time and coordinated with the engine speed.

Vehicle Dynamics and Brake System Models

The Vehicle Dynamics (NADSdyna) Computer Simulation determines vehicle motions and control feel conditions in response to driver control actions, road surface conditions, and aerodynamic disturbances. Vehicle responses are computed for commanding the Visual, Motion, Control Feel, and Auditory Systems.

The vehicle dynamics model used in this project was developed by VRTC for the 1992-GMC truck manufactured by Volvo GM Heavy Truck, model WIA64T and a 1992 Fruehauf trailer model FB-19.5NF2-53 [2, 3].

The torque characteristics of commercial vehicle brakes have been studied by numerous investigators. Formulation of the brake model based on fundamental understanding of the development of the instantaneous brake torque as influenced by pressure, temperature, sliding velocity, work history, temperature gradients, and other factors has not been achieved. Recent research has been directed by treating the brake effectiveness as empirical functions. The brake models used in NADS are primarily empirical, based on fitting experimental data obtained from brake dynamometer and field test data (Figure 12).

The objective of this research is to study the functional effects of three different brake configurations:

- Standard truck where S-cam brakes are installed on all wheels
- Enhanced truck where only the steer axle is equipped with a higher capacity version of an S-cam brake
- Disc truck where all the wheels of the tractor are equipped with disc brakes.

The brake parameters were set such that severe braking from 60 mph (97 kph) provides a stopping distance of 307 ft (93.6 m) for standard brake, 256 ft (78.0 m) for enhanced brakes, and 215 ft (65.5 m) for disc brake (as shown in Figure 13). This is a reduction of stopping distance of 17% and 30% if the standard S-cam brake system is replaced with the enhanced and disc systems respectively. In this study all these systems are mounted on the same tractor-trailer model [9].

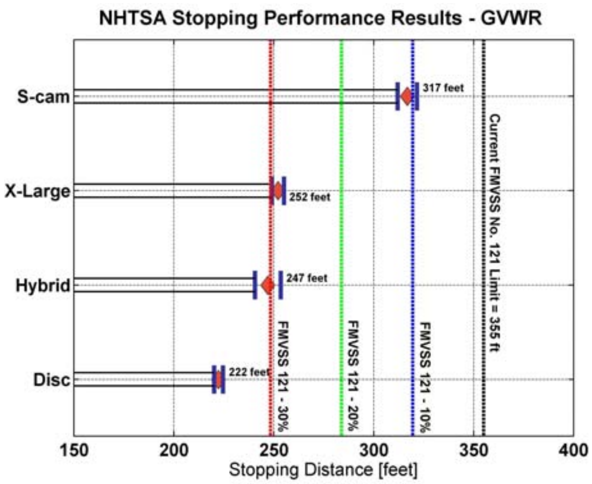

Figure 12 Brake performance measured by VRTC for a typical tractor-trailer with different brakes (x-large and hybrid in the graph refer to the enhanced brakes in this paper).

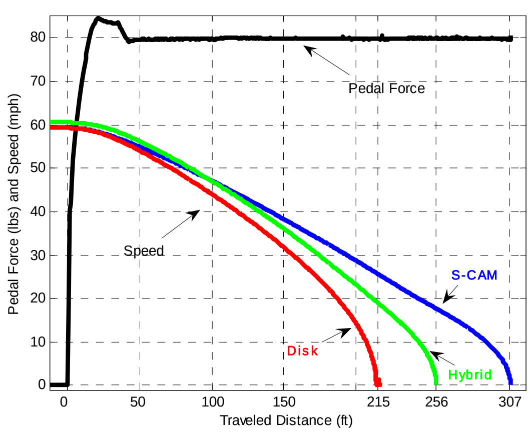

Figure 13. Brake performances on NADS.

PROCEDURE

The total number of participants in this study was 108. Upon arrival at the NADS facility, participants were given a verbal overview of the Informed Consent Document and were then asked to read and sign the document. Next, the participants completed the NADS Driving Survey and were given instructions on the monetary incentive scheme. Participants were assigned a single brake system condition for their participation. The order of scenario presentation was varied systematically across participants.

Prior to beginning treatment drives, participants received a familiarization practice drive. This drive provided them experience with the vehicle's brake system's capabilities, and also familiarity with shifting the transmission.

After each scenario drive, participants were told the amount of incentive they earned and the amount was recorded on a data sheet. After all driving was completed, participants completed the simulator sickness questionnaire. After the simulator was docked, the participant was escorted to the participant prep area, offered a snack or beverage, and given an opportunity to ask questions. Participants completed a realism survey and a post-drive questionnaire.

Finally, the participant was paid an amount consisting of the sum of the base pay plus incentive pay. The participant signed the payment voucher, describing how compensation was related to driving performance. The participant was then escorted to the exit.

INCENTIVES

Drivers were given incentives to maintain a constant velocity within ± 3 mph (5 kph) of the target speed. A driver could earn a total $3.00 per drive based on the percentage of time that his or her speed remained within the specified range. Generally, a short period immediately after the scenario start and the event itself were excluded from this calculation.

DATA REDUCTION

Each event was divided into five segments using six different time points and the final reduced data file spreadsheet included one line per event. These time points were T1 (event onset) through T6 (event completion) and are defined below.

- **T1:** Event onset (scenario specific)
- **T2:** Initiation of accelerator pedal release, determined by comparing whether the current accelerator pedal position to a running mean pedal position over one second of running time falls below a predefined threshold.

- **T3:** Completion of accelerator pedal release (when accelerator pedal position drops below 5% of full range).
- **T4:** Initiation of brake pedal depression (when brake pedal force exceeds 2.0 lbs).
- **T5:** Application of maximum brake pedal force.
- **T6:** Completion of the braking event.

The following variables were collected: longitudinal distance between each event, velocity and acceleration at each event, gear shift position, accelerator pedal position, brake pedal force, steering angle at T1, reaction time between events, braking distance from T4 to T6, total stopping distance from T1 to T6, maximum brake pedal force (brake pedal force at T5), mean and median brake pedal force from T4 to T6, mean deceleration rate, maximum deceleration rate, time from T1 to maximum deceleration, maximum absolute value of steering wheel angle from T1 to T6, time to collision at T1 (assuming driver's speed doesn't change, time before a collision would occur), distance to collision object at T1, Final distance to collision object at T6, collision (1 = yes, 0 = no), collision object name, collision velocity; relative velocity at time of collision, heading angle of tractor at each T, articulation angle at each T, maximum articulation angle, time of maximum articulation angle from T1, tractor accelerations in x, y, and z directions at each T, trailer accelerations in x, y, and z directions at each T (18 variables in all), tractor yaw rate at each T, and trailer yaw rate at each T.

Collisions with other vehicles were enumerated for each scenario. Collisions could occur with a single oncoming vehicle or with vehicles parked alongside the road. To provide better discrimination as to the meaning of collisions, the reduced data contained individual indicators of collision with each vehicle in each scenario.

RESULTS

Each event was analyzed separately using a similar statistical approach based on comparing drivers' reaction times, stopping distances and number of collisions. Reaction time was defined as the time interval between the time the event starts and the driver activating the brake. The main performance measures were based on whether there was a vehicle crash or not, the delta speed in case of a crash and the stopping distance if not. The hypothesis to be confirmed is that the average reaction time for drivers is statistically similar across the brake conditions. That is, drivers for the S-cam, enhanced brakes, and disc brakes perceive the obstacles with no significant variations. Reaction time was deemed as being the same if the mean values were within 0.3 seconds of each other. The second hypothesis is that there are more collisions (and with higher delta speed) with the S-cam brakes then with the other two systems. Delta speed is an indication of the collision severity; higher speeds indicate higher kinetic energy and consequently, higher severity collision. Drivers' braking efforts were compared for the three systems in order to confirm that reductions in collisions were the result of better stopping performance rather than a reduction of driver braking effort (pedal force) when driving a truck with an S-cam system.

Right Incursion

The collision information data listed in Table 1 show that the number of collisions decreased slightly when the S-cam brake system is replaced with the disc brake system.

The average stopping distance for the S-cam brake system was higher than for the other two systems (Table 2 and Figure 14) despite the drivers exerting more effort in braking as can be seen on the mean braking force in Figure 15. The difference between the three braking systems was statistically significant as the p-values included in the figures suggest. The distance traveled by the drivers to perceive the obstacle on the road (Figure 16), time of action between obstacle perception and the starting of hard braking (Figure 17), lane deviation (Figure 18) and the speed at the onset of hard braking (Figure 19), show that the experimental procedures were well controlled and these human reaction/perceptual natural differences were not a factor in the differences seen in the number of crashes and stopping distances (summary in Table 3).

Table 1.
Right Incursion Collisions

Brake Type	Collision With Incursion
S-cam	**1**
Enhanced	**1**
Disc	**0**

Table 2.
Right Incursion Stopping Distance

Brake Type	Mean ft (m)	P
S-cam	**292 (89)**	**0.023**
Enhanced	**270 (82.3)**	
Disc	**262 (79.8)**	

Table 3.
Right Incursion Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**53.3 (85.7)**	**53.7 (86.4)**	**52.8 (84.9)**	**0.234**
Distance before T1 ft (m)	**47 (14.3)**	**49 (14.9)**	**48 (14.6)**	**0.322**
Time of Action (T1-T4) sec	**0.93**	**0.90**	**0.95**	**0.708**
Speed Before Heavy Braking mph (kph)	**52.1 (83.8)**	**52.6 (84.6)**	**52.6 (84.6)**	**0.192**
Lane Deviation ft (m)	**3.2 (1.0)**	**2.6 (0.8)**	**2.6 (0.8)**	**0.545**

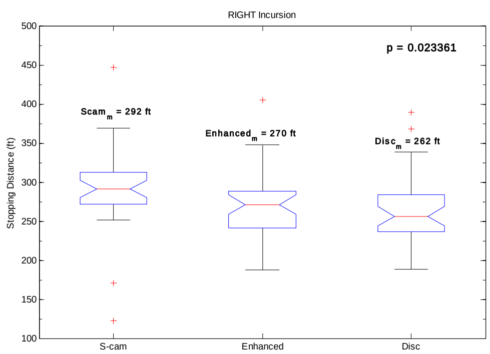

Figure 14. Right incursion stopping distance.

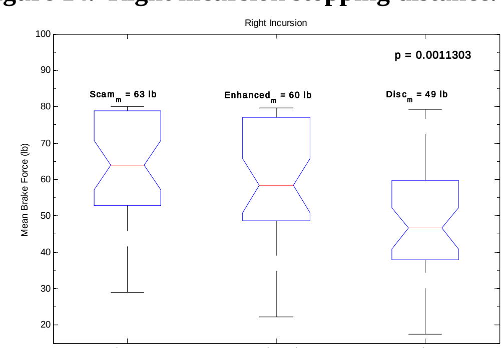

Figure 15. Right incursion drivers' braking efforts.

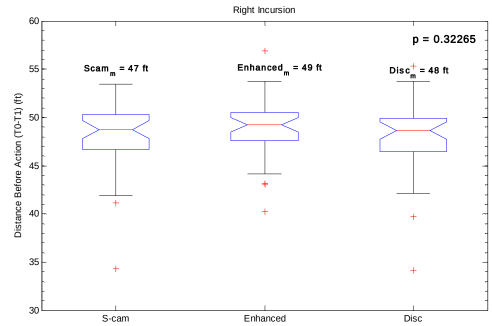

Figure 16. Right incursion drivers' distance traveled before action.

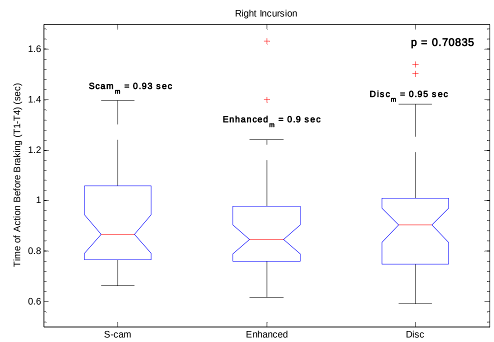

Figure 17. Right Incursion Drivers' Time to Action.

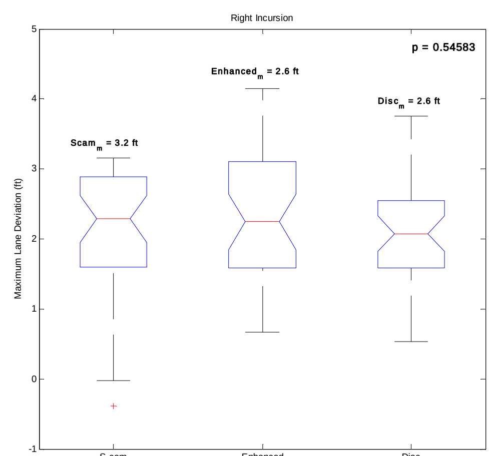

Figure 18. Right incursion drivers' lane deviation.

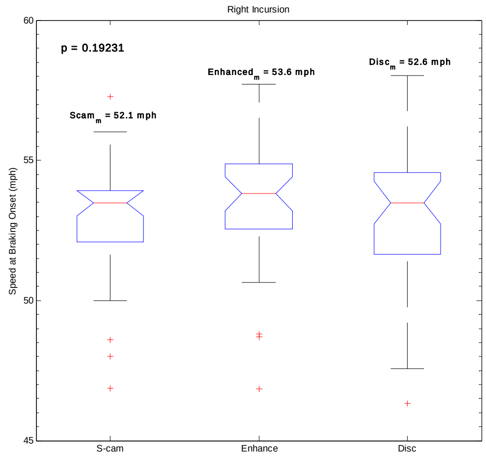

Figure 19. Right incursion drivers' speed at heavy braking onset.

Left Incursion

The left incursion analysis followed the methodology used for the right incursion, and Table 4 provides the number of crashes for each brake systems. There were fewer collisions with the enhanced and disc system than with the S-cam. Tables 5 and 6 and Figures 20 – 26 illustrate driver responses for this scenario.

Table 4.
Left Incursion Collisions

Brake Type	Collision	Speed mph (kph)	P
S-cam	**13**	**24 (38.6)**	
Enhanced	**4**	**23 (37.0)**	**0.268**
Disc	**11**	**17 (27.3)**	

Table 5.
Left Incursion Stopping Distance

Brake Type	Mean ft (m)	P
S-cam ft	**340 (103.6)**	
Enhanced ft	**309 (94.2)**	**0.05**
Disc ft	**322 (98.1)**	

Table 6.
Left Incursion Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**53.0 (85.3)**	**53.3 (85.8)**	**52.9 (85.1)**	**0.45**
Distance before T1 ft (m)	**216 (65.8)**	**213 (64.9)**	**212 (64.6)**	**0.74**
Time of Action (T1-T4) sec	**1.461**	**1.35**	**1.62**	**0.07**
Speed Before Heavy Braking mph (kph)	**52.7 (84.8)**	**53.1 (85.4)**	**52.5 (84.5)**	**0.29**
Lane Deviation ft (m)	**2.9 (0.9)**	**2.8 (0.85)**	**2.7 (0.8)**	**0.45**

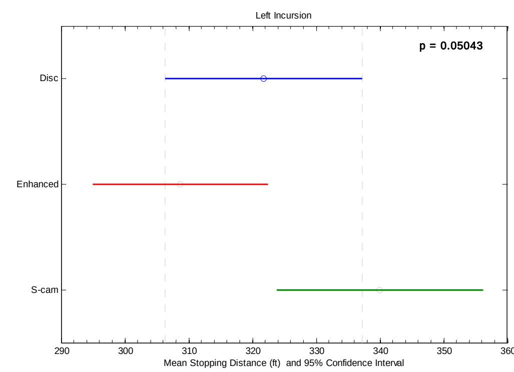

Figure 20. Left incursion stopping distance.

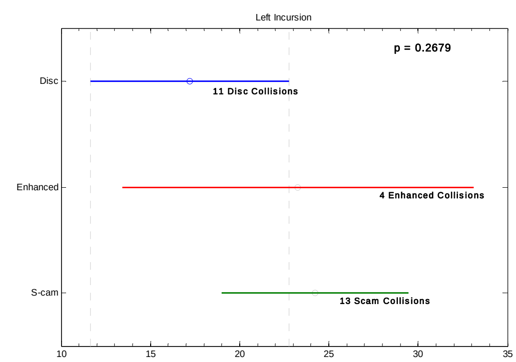

Figure 21. Left incursion collision speed.

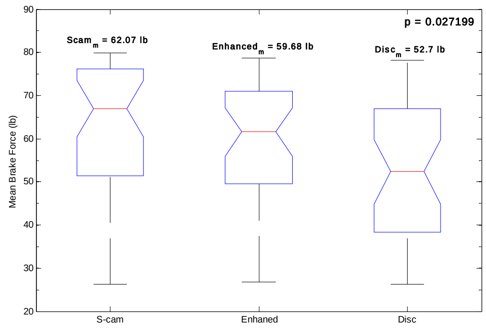

Figure 22. Left incursion drivers' braking efforts.

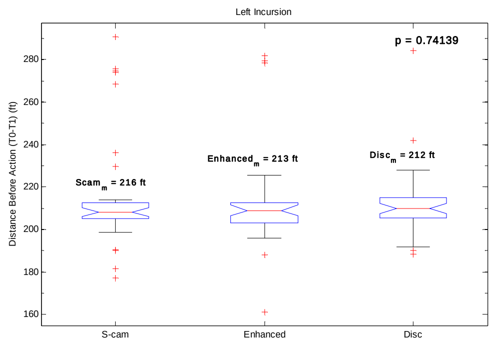

Figure 23. Left incursion drivers' distance traveled before action.

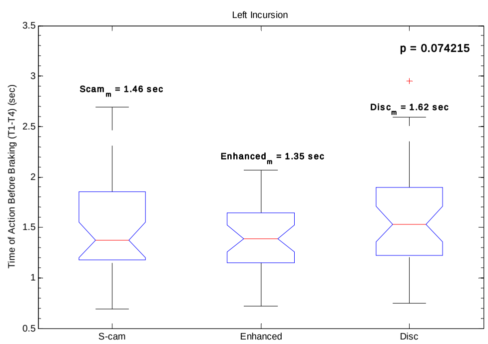

Figure 24. Left incursion drivers' time to action.

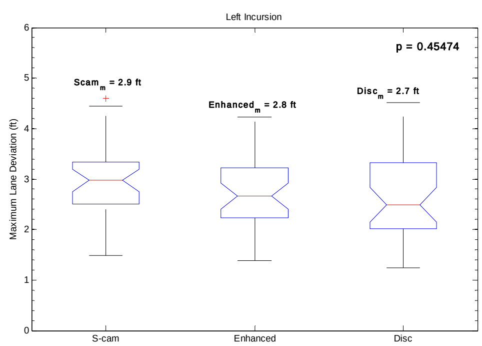

Figure 25. Left incursion drivers' maximum lane deviation.

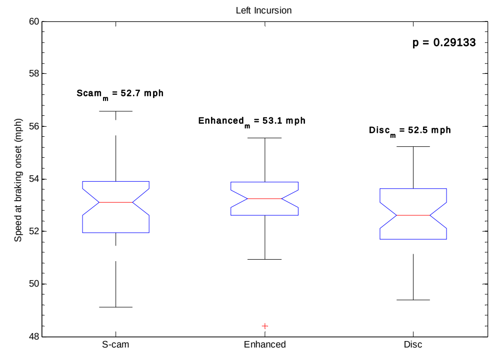

Figure 26. Left incursion drivers' speed at heavy braking onset.

Stopping Event

This event collision data are provided in Table 7 and show that there are more collisions with S-cam brakes and the collision speed is greater than with the other systems. The Enhanced and the Disc brakes are showing about the same number of collisions, with lower collision speed for the disc brakes. Tables 8 and 9 and Figures 27 – 30 illustrate driver responses for this scenario.

Table 7.
Stopping Event Collisions

Brake Type	Collision	Speed mph (kph)	P
S-cam	**22**	**23.0 (37.0)**	**0.069**
Enhanced	**9**	**18.9 (30.4)**	
Disc	**12**	**15.7 (25.3)**	

Table 8.
Stopping Event Stopping Distance

Brake Type	Mean ft (m)	P
S-cam	**336 (102.4)**	**0.007**
Enhanced	**281 (85.6)**	
Disc	**296 (90.2)**	

Table 9.
Stopping Event Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**50.8 (81.7)**	**52.0 (83.7)**	**50.9 (81.9)**	**0.157**
Distance before T1 ft (m)	**4.8 (1.5)**	**4.8 (1.5)**	**4.6 (1.4)**	**0.285**
Time of Action (T1-T4) sec	**1.6**	**1.32**	**1.63**	
Speed Before Heavy Braking mph (kph)	**51.0 (82.0)**	**52.0 (83.7)**	**51.0 (82.0)**	**0.148**
Lane Deviation ft (m)	**2.0 (0.6)**	**2.1 (0.64)**	**2.0 (0.6)**	**0.843**

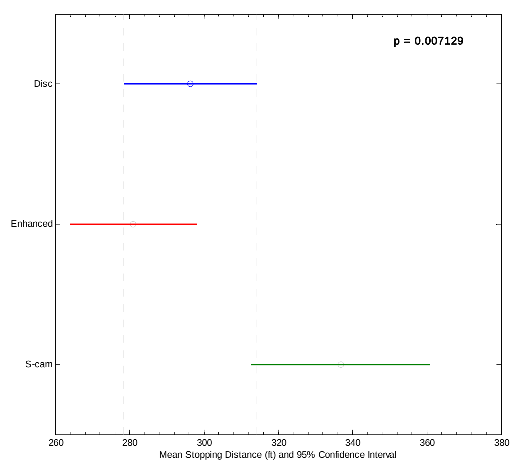

Figure 27. Stopping event stopping distance.

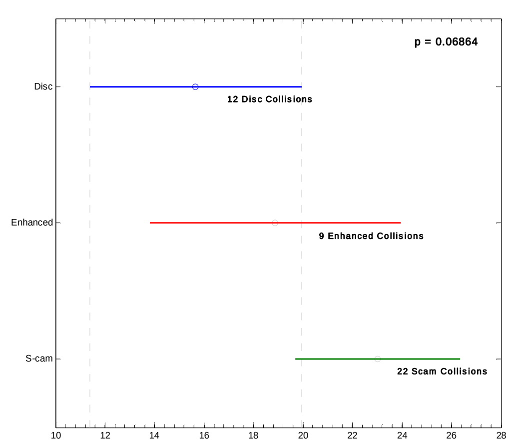

Figure 28. Stopping event collision speed.

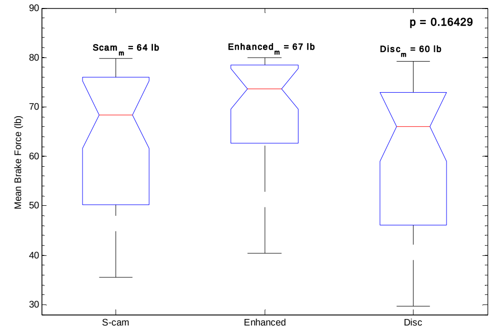

Figure 29. Stopping event drivers' braking efforts.

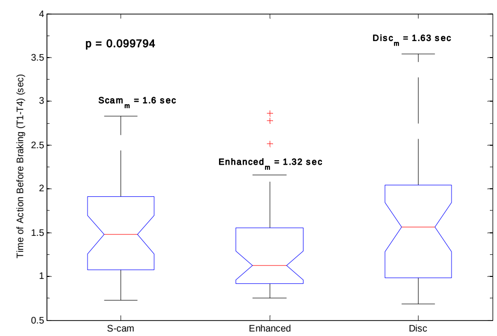

Figure 30. Stopping event drivers' time to action.

Stopped Event

This event involved driving at a high speed close to 70 mph (110 kph) and is considered to be the most severe of the three scenarios. Some drivers took evasive action by steering to the right. For those drivers who remained in their lane, the collision data listed in Table 10 show that those with the disc brake system had fewer collisions than those with the other two systems. The severity of this experiment showed that only the disc brake system was able to reduce the number of collisions significantly and the collision speed. With less braking effort, drivers with the disc brake system were able to stop within a shorter distance and had fewer collisions. Tables 11 and 12 and Figures 31 – 35 illustrate driver responses for this scenario.

Table 10.
Stopped Event Collisions

Brake Type	Collision	Speed mph (kph)	P
S-cam	**Stopped: 15** **Other: 1**	**32 (51.5)**	**0.06**
Enhanced	**Stopped: 22** **Other: 1**	**28 (45.0)**	
Disc	**Stopped: 7** **Other: 3**	**23 (37.0)**	

Table 11.
Stopped Event Stopping Distance

Brake Type	Mean ft (m)	P
S-cam	**909 (277.0)**	**0.039**
Enhanced	**657 (200.2)**	
Disc	**560 (170.7)**	

Table 12.
Stopped Event Drivers' Performances Before Heavy Braking

Type	S-cam	Enhanced	Disc	P
Entry Speed mph (kph)	**67 (107.8)**	**68 (109.4)**	**67 (107.8)**	**0.046**
Distance before T1 ft (m)	**86 (26.2)**	**97 (29.6)**	**80 (24.4)**	**0.220**
Time of Action (T1-T4) (sec)	**3.0**	**2.2**	**3.0**	**0.520**
Speed Before Heavy Braking mph (m)	**67 (107.8)**	**68 (109.4)**	**66 (106.2)**	**0.097**
Lane Deviation ft (m)	**3.7 (1.1)**	**3.3 (1.0)**	**3.2 (0.97)**	**0.552**

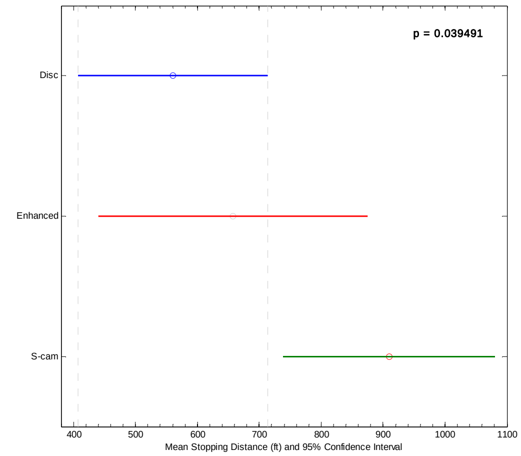

Figure 31. Stopped event stopping distance.

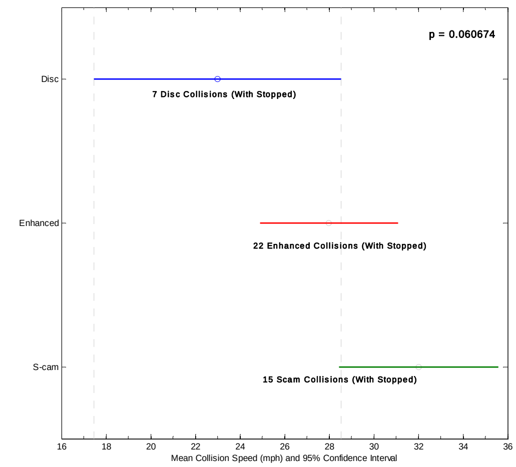

Figure 32. Stopped event collision speed.

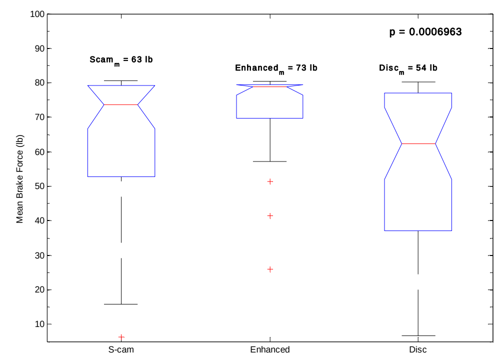

Figure 33. Stopped event drivers' braking efforts.

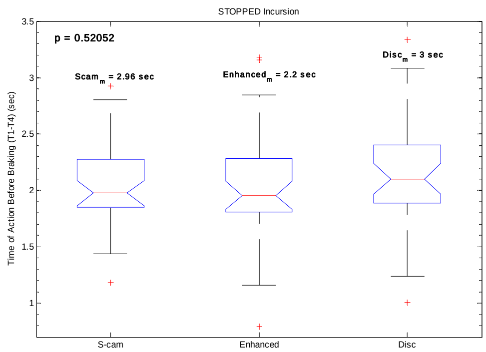

Figure 34. Stopped event drivers' time to action before braking.

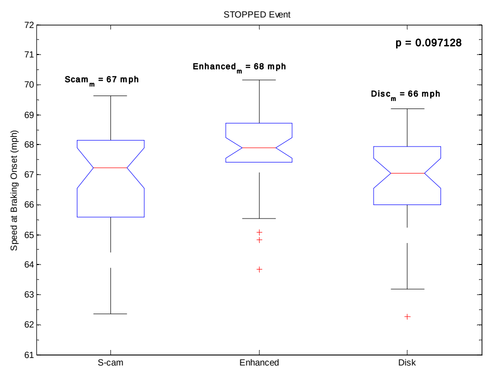

Figure 35. Stopped event drivers' speed at hard braking onset.

CONCLUSION

Based on the results presented here, the hypothesis that a brake system that provides a shorter stopping distance in an emergency braking event would reduce crashes and fatalities is valid. The type of braking system had no statistical effect on driver behavior prior to braking. The experiment used a validated virtual environment with high fidelity and showed systematically within a reasonable statistical confidence that professional drivers using either enhanced or disc brake systems were able to avoid many collisions. In an extreme emergency braking event at high speed, drivers using the disc brake system avoided collisions better or had reduced collision severity than those using the enhanced brake system.

ACKNOWLEDGEMENT

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PASSENGER, GOODS AND AGRICULTURAL VEHICLE SAFETY - EFFECTIVENESS OF EXISTING MEASURES AND RANKING OF FUTURE PRIORITIES IN THE UK

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Paper Number 07-0452

ABSTRACT

Larger vehicles, such as goods vehicles with a gross vehicle weight in excess of 3500kg or passenger vehicles with more than 16 seats, are involved in fewer accidents per billion vehicle kilometers travelled than passenger cars. However, these larger, heavier vehicles are involved in more fatal accidents per billion vehicle kilometers than passenger cars. The UK Department for Transport is currently reviewing its priorities for safety of large goods vehicles and large passenger vehicles. Phase 1 of the review has included an extensive literature search to identify how previous changes in regulation have affected casualty figures and to identify the predicted benefits from more recent research. Phase 2 of the review includes analysis of accident data, including STATS19 (GB national statistics), European CARE database and other UK based studies such as the Heavy Vehicle Crash Injury Study (HVCIS), Co-operative Crash Injury Study (CCIS) and the On-the-Spot (OTS) study. HVCIS is the only UK study that routinely collects nationally sampled accident data specifically relating to larger vehicles and plays a pivotal role in this review.

The project will identify the most cost effective countermeasures for larger vehicles taking predicted casualty reduction, cost of implementation, technical feasibility and likely date of introduction into account. For the first time in the UK, statistical modeling techniques, which are currently used to predict national casualty reductions, are used specifically for the analysis of casualties in accidents involving larger vehicles only.

This paper reports the findings of the analysis, to date, including analysis of the HVCIS fatal accident database which contains over 1800 fatal accident cases involving larger vehicles. Fatalities are comprised of large vehicle occupants and their opponents. The paper features pedestrian impacts as an example of one of the potential key areas of interest that has been identified by this research.

INTRODUCTION

This project has been carried out to assist the UK Department for Transport to help further improve road safety in the UK beyond 2010. The project also identifies some measures that could assist in meeting the 2010 casualty reduction targets. The project assesses the performance of existing safety measures and identifies where future road accident casualty savings can be made. The aims of the project are to determine how previous research and resulting measures have performed, to identify and prioritise current issues and to propose where best to target resources to deliver further worthwhile casualty savings.

The vehicle types covered by the research are:

- Large passenger vehicles (LPVs) – passenger vehicles with 17 or more passenger seats
- Heavy goods vehicles (HGVs) – goods vehicles with a gross vehicle weight of more then 3.5tonnes
- Light commercial vehicles (LCVs) – goods vehicles with a gross vehicle weight of up to 3.5 tones inclusive
- Agricultural vehicles
- Other motor vehicles (OMVs) – vehicles that are not classified as goods vehicles or passenger vehicles such as refuse lorries, mobile cranes, fire engines

METHOD

The project consists of three phases: review of literature, accident data analysis and consideration of countermeasures.

A review of literature relating to past research and regulatory activity was carried out to identify a list of significant changes in regulation or standard practice that might have influenced heavy vehicle safety. The review focused on estimated benefits prior to changes in regulation and evidence of actual benefits that were achieved. The areas covered by the review included, but were not limited to:

- Introduction of rear underrun protection
- Fitment of seatbelts to coaches and minibuses
- Changes to braking regulations for agricultural tractors
- Mandatory fitment of ABS to the larger categories of buses and goods vehicle

Accident data analysis used a combination of data sources. STATS19 data was used for the analysis of trends and for analysis of the effect of previous changes in regulation. Trend analyses were based on the period 1995-2005. The contribution of HGVs, LPVs and LCVs towards the UK casualty reduction targets was also analysed. Detailed analysis was carried out using STATS19 and the HVCIS fatal accident database. STATS19 data for the period 2003-2005 was used for this analysis. The HVCIS data contained accidents from 1997-2002. CCIS and OTS data were also analysed, particularly for consideration of car-derived vans. The CARE database is the disaggregate database of road accident data that is maintained by the European Commission, bringing together the national databases of the Member States. Data covering the period 2000-2004 was used to consider the UK accident situation with respect to the European context.

The data from the detailed STATS19 analysis was used to create a list of casualty groups that are injured in accidents involving large goods vehicles, large passenger vehicles or agricultural vehicles, either as occupants of those vehicle types or as opponents to those vehicle types. The casualty groups were not mutually exclusive, with some groups being sub-sets of the higher level groups, forming a hierarchical structure, an example of which is shown in Figure 1.

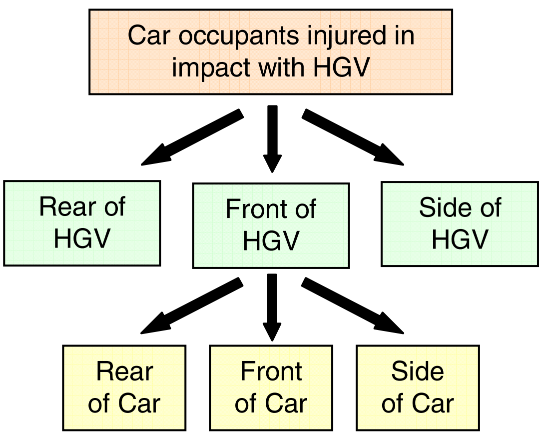

Figure 1. Hierarchy of casualty groups.

Where the casualty was the *occupant* of a commercial vehicle, for example an HGV occupant, the hierarchy was different to that for the *opponents* of the commercial vehicles, for example:

- HGV Occupant
  - HGV occupant in single vehicle accident
  - HGV occupant in rollover
  - HGV occupant in impact with other vehicle
  - HGV occupant in impact with object

The number of levels in the hierarchy was dependant on the number of casualties, in general where the number of casualties was less than ten, the group was not divided any further. The groups were not split any further than illustrated in Figure 1. Some examples of the lower level casualty groups are:

- Car occupants involved in crashes where the front of the car impacts the rear of the HGV
- Pedestrian impacts to front of LPV
- Two wheeled motor vehicle (TWMV) users in impacts between the side of the TWMV and the side of the HGV
- Pedal cyclist casualties in impacts with a minibus
- Injured HGV occupants in impacts with another HGV
- Injured LPV occupants in impact with another vehicle
- Injured agricultural vehicle occupants in rollover accidents

In order to help prioritise the action for each casualty group it was necessary to rank the importance of each group. This can be achieved in a variety of ways, for example using the total number of casualties or the number of fatalities. The UK casualty reduction targets are expressed in terms of target reductions in killed and seriously injured (KSI) casualties and it was decided that the ranking should be related to this target. However, it is possible that two casualty groups could have identical numbers of KSI casualties but within that group one could have a higher proportion of fatalities than the other. To account for this phenomenon the casualty groups were ranked in order of the societal cost of the KSI casualties in each group. The societal costs used, were those defined by the UK Government as shown in Table 1.

Table 1.
UK societal costs (TSO, 2006a)

Casualty Severity	Cost per Casualty
Fatal	£1,428,460
Serious	£160,510
Slight	£12,580

The final phase of the research considers measures that could be introduced to reduce the number or severity of road user casualties. The main focus of this paper is the accident data analysis phase of the research.

RESULTS

Literature Review

The literature review showed that most of the measures that had been implemented in the past had considerable justification, but were not necessarily expressed as specific lives saved. Changes made to agricultural vehicles were the exception to this. Although research related to safety systems such as rollover protection was reviewed, no estimated benefits were identified for the changes to weights and dimensions of agricultural vehicles or for the introduction of rollover protection systems for on road accidents in the UK. This is likely to be related to the low frequency of on road agricultural vehicle accidents and that cost benefit analyses for these vehicle types are often based on their off road use. There were however, estimated benefits for the fitment of seatbelts to agricultural vehicles for on-road accidents.

The more recent research tended to have more comprehensive predictions for potential benefits, and almost all new proposals for measures have an estimate of casualty reductions. However, the variations in the way that the benefits were predicted make direct comparisons difficult. Examples of these differences relate to the use of different samples, fatality and/or all injury reduction, predictions for different countries or for the EC and the year of prediction and associated variations in absolute casualty numbers.

There were only a few measures for which a retrospective evaluation has been carried out after implementation. A detailed retrospective evaluation can be difficult to perform because it is hard to separate the effects of multiple measures, for example improved passenger car crashworthiness and rear underrun protection. Overall, the package of measures taken appears to have been effective because accident and fatality rates have reduced substantially.

Analysis of the Effect of Previous Changes

A comparative analysis of STATS19 data before and after the introduction of safety changes was carried out to identify if there has been an effect of the changes on the accident trends. The safety changes to be assessed were selected from the list of safety measures identified during the literature review. The analysis is limited by data that is available for analysis in STATS19 and also by sufficient fleet penetration of the safety feature, for example it was not possible to assess the effectiveness of the fitment of speed limiters or more recent changes such as improved field of view from HGVs. Therefore three changes were selected for the analysis:

1. Rear underrun protection
2. Rollover crashworthiness of LPVs
3. ABS fitment on HGVs

This paper reports the investigation of rear underrun protection as an example. This analysis does not attempt to separate the influences of a number of different safety changes that occurred in the same time period, for example increased seatbelt wearing and improvements to structural crashworthiness of passenger cars as well as the rear underrun protection.

An analysis of the effects of introducing front underrun protection was carried out by comparing the vehicles fitted with front underrun protection involved in KSI accidents to those without front underrun protection in accidents from 2003 to 2005. The exact fitment of front underrun protection to vehicles involved in accidents is unknown, however an approximation was used based on date of registration of the HGVs. The data is summarised in Table 2.

Table 2.
Proportion of fatally and seriously injured car occupants in impacts with the front of HGVs by year of HGV registration

	HGV First Registered	
	Pre-2003	**2003-2005**
Number	215	72
Proportion Killed	4.2%	5.8%
Proportion KSI	15.6%	17.9%

There is no significant difference between the casualties for the two groups of HGV, however the group of HGV registered 2003-2005 is small and, hence, the analysis should be repeated when more data is available. Using the year of registration is an approximation for identifying vehicles likely to be fitted with front underrun protection. However some vehicles will have been fitted with front underrun protection prior to 2003 and some vehicles registered after 2003 may be exempt.

When considering the effectiveness of rear underrun protection two methods were used:

1. Comparison of accident injury severities before and after introduction of regulation
2. Consideration of the involvement of vehicles that are exempt from fitting underrun protection in accidents

A third method was also considered. This involved statistical modelling, comparing the proportion of casualties killed in impacts with the rear of the HGV compared with those killed in other impacts with the HGV. However, this time series analysis proved inconclusive because rear underrun protection was only fitted to new vehicles so that the during the time taken for full fleet penetration there have been numerous other changes influencing the accident pattern.

Comparison of accident data – An initial indication of the effectiveness of rear underrun protection may be gained by considering how the injury severity distribution of car occupant casualties in frontal impacts with the rear of an HGV has changed. Table 3 summarises the severity distribution of car occupant casualties for a period before the introduction of rear underrun protection (1983) and for a number of periods after the requirement to fit rear underrun protection.

Table 3.
Car occupant casualties in accidents where the front of the car collided with the rear of an HGV

Time Period	Average number (%) of casualties				Annual Total
	Fatal	Serious	Slight	KSI	
1979 to 1982	93 (3.6)	650 (25.4)	1820 (71.0)	2563 (29.0)	2563
1989 to 1992	99 (2.7)	582 (15.7)	3026 (81.6)	3707 (18.4)	3707
1999 to 2002	54 (1.3)	364 (8.5)	3790 (88.7)	4271 (11.3)	4271
2002 to 2005	47 (1.3)	263 (7.1)	3412 (91.7)	3722 (8.3)	3722

Table 3 shows that the number of car occupant fatalities initially increased after the introduction of rear underrun protection and then decreased. However, the proportion of casualties that are killed or seriously injured decreased within the initial 10 year period and has then continued to decrease. The largest reduction was in the initial period considered. This suggests that the introduction of rear underrun protection has provided some benefit, however seatbelt use and crashworthiness of passenger cars are likely to have been a substantial influence.

Consideration of exempt vehicles – The effectiveness of a measure can be assessed by comparing the involvement of vehicles fitted with the equipment compared to those without it. For rear underrun protection, this information is not available, however information about the involvement of vehicles exempt from fitting the equipment can be used as a proxy. Information about the body types of rigid HGVs is recorded in transport statistics (TSO, 2006a). Using the body type data it is possible to estimate the percentage of the vehicle fleet (for rigid vehicles only) that are exempt from fitting rear underrun protection. Based on specific vehicle exemptions outlined in the UK Construction and Use Regulations 1986 (HMSO, 1986), it has been assumed that the following vehicle categories are exempt from fitting rear underrun protection:

- Tipper
- Concrete mixer
- Car transporter
- Tractor
- Mobile plant

There are a number of vehicles where the body type is not known or classified as “other”. Some of these may be vehicles that are also exempt from fitting rear underrun protection, however it is not possible to quantify this. Therefore upper and lower boundaries for the number of exempt vehicles can be produced. The upper boundary assumes that all the “other” and not known vehicles are exempt and the lower boundary assumes that they are not exempt. The mid value applies the ratio of exempt to not exempt vehicle to those where the exemptions are not known or “other”. This data is summarised in Table 4.

Table 4.
Vehicle exemptions

	Vehicle fleet, average 2002-2004		
	Lower	Mid	Upper
Exempt Vehicles	60.5	62.6	71.2
Not Exempt	258.2	256.1	247.5
Total	318.7	318.7	318.7
Percentage Exempt	19.0%	19.5%	22.3%

Using STATS19 data that is linked to vehicle registration data, it is possible to identify, by body type, vehicles that are likely to be exempt from fitting rear underrun protection that have been involved in accidents in the UK. Table 5 summarises the number of Rigid HGVs that were impacted from the rear by the front of a car, separating those that were exempt from fitting rear underrun protection based on the assumptions described above.

Table 5.
Rigid HGVs involved in accidents where the front of a car collided with the rear of the HGV by exemptions

	Number of Rigid HGVs by maximum severity of car occupant injured				
	Fatal	**Serious**	**Slight**	**KSI**	**Total**
Exempt	7	19	216	26	242
Not Exempt	10	26	278	36	314
Total	17	45	494	62	556
% Exempt	41.2	42.2	43.7	41.9	43.3

From Table 5 it is possible to compare the proportion of vehicles that were exempt from fitting rear underrun protection and involved in accidents with the proportion of vehicles in the fleet that were estimated as being exempt from fitting rear underrun protection. Comparing Table 5 with Table 4 it is clear that a higher proportion of rigid vehicles that are involved in accidents where car occupants are injured in frontal collisions with the rear of a rigid HGV are exempt from fitting rear underrun protection, 41.9% for KSI casualties compared with the vehicle stock of between 19.0% and 22.3%.

Trend Analysis

In order to determine future safety priorities, it is important to consider the accident data in the wider context of the vehicle fleet on the road in the UK.

- Figure 2 shows a ten year trend for distance travelled by the type of vehicle used.

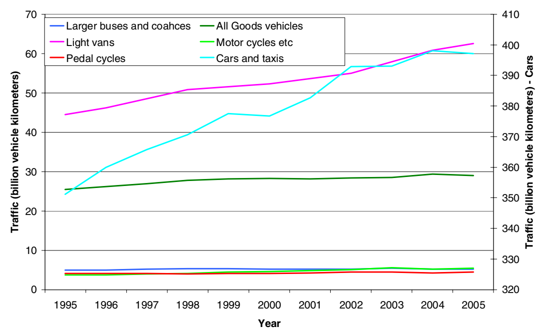

Figure 2. Trends in distance travelled by vehicle type[1].

- It is clear that there is a large growth in traffic from the use of passenger cars, with approximately a 15% increase in ten years. However, the growth of LCV traffic has increased by approximately 40% in the same period. There has also been approximately a 20% increase in goods vehicle traffic.

- Figure 3 summarises the current progress towards the 2010 casualty reduction targets.

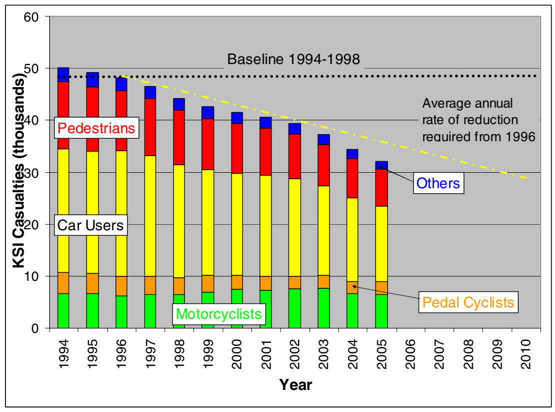

Figure 3. Progress towards casualty reduction targets (TSO 2006a and TSO 2000).

- Figure 3 shows that despite the growth in traffic, the reduction in casualties is on target.

- As well as looking at the overall trends in the use of vehicles and casualties, it is also possible to look at how large goods vehicles and large passenger vehicles have contributed towards meeting the UK's 2010 casualty reduction target. This is achieved by calculating the casualty rate in LCV (LPV or HGV) accidents relative to the overall casualty rate using equation 1.

$$\text{relative casualty rate} = \frac{\text{casulaties in HGV accidents per billion HGV kilometers}}{\text{casulaties in all accidents per billion vehicle kilometers}} \quad (1)$$

- Figure 4 shows how LCVs have contributed to the UK casualty reduction targets. A horizontal line with a value of one would indicate that accidents involving LCVs have the same casualty rate as other vehicle types and have been contributing to the casualty reduction targets in line with accidents involving other types of vehicle.

[1] Notes: 1) Decline in car use in 2000 due to fuel dispute 2001 figures affected by foot and mouth
2) Change to methodology for collecting pedal cycle data improved, affects data for 2004 and 2005
3) Light vans with GVW≤3.5tonnes
4) All goods vehicles with GVW>3.5tonnes

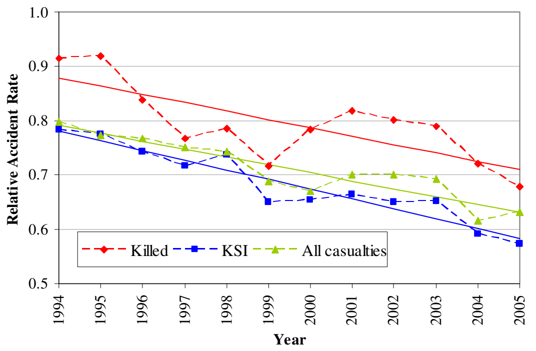

Figure 4. Contribution of LCVs to UK casualty reduction targets.

- Figure 4 shows that accidents involving LCVs have a lower casualty rate than for all accidents and that the casualty rate fell more than the casualty rate for all vehicles. This indicates that accidents involving LCVs have made a positive contribution towards the UK casualty reduction targets.
- LPVs have a casualty rate that is 3.5 – 5 times that of all of accidents. The relative KSI rate has risen slightly, so although the KSI rate fell by 44% between 1994 and 2005, the KSI rate for all accidents fell farther, by 46%. This indicates that accidents involving LPVs have slightly slowed progress toward the casualty reduction target for KSI. Conversely, the relative Killed rate tended to fall over this period. The rate of all casualties rose relatively fast throughout this period.
- HGV accidents tend to be severe, which is reflected in the high relative rate for killed, some three times that of the rate for all accidents. The killed rate fell by about 10% between 1994 and 2005 and the relative KSI rate also fell, by about 5%, contributing to the casualty reduction targets at a higher rate than other vehicle types.

Analysis of European accident data

At present, data are available for the 15 pre-Accession states, although access to German data is not permitted[2]. TRL has access to CARE, and has downloaded data for accidents involving LPVs, HGVs and LCVs. Although CARE includes full records of non-fatal accidents and casualties, in practice international comparisons only make use of data for fatal accidents and casualties because of inconsistent reporting standards and definitions among the Member States.

The aim of this analysis is to provide a European context for the British casualty data. Three groups of fatalities have been analysed: those in accidents that involve one or more LCV, one or more HGV and one or more LPV. Two types of international comparison have been made: of the proportion of the national fatality total occurring in these accidents and of the fatality risk based on accident rate. In most Member States, traffic data are not available comparable to the level of the British traffic data so comparisons of risk are based on measure of the rate per million population.

The overall fatality rate in the UK is amongst the lowest in Europe, so the UK would be expected to rank better on the rate-based comparison than the proportion-based comparison. Figure 5 illustrates the fatality rate per million population in the three groups of accident that were analysed.

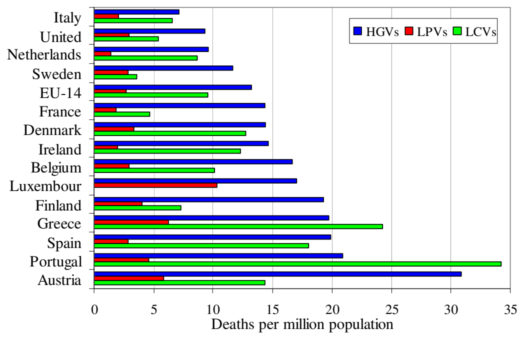

Figure 5. National fatality rates per million population in LCV, HGV and LPV accidents, 2000 – 2004[3].

The UK's LCV and HGV rates are low in comparison to other EU countries. However, UK LPV rate is around the median. When the proportion of fatalities that are caused in accidents involving LPVs, HGVs and LCVs are considered, accidents involving LPVs and HGVs are relatively a more important accident group when compared to the average for the EU-14 (15 pre-accession states but excluding Germany). Accident involving LCVs are about average.

Figure 6 summarises the distribution of fatalities for accidents involving HGVs.

[2] The UK data in CARE are the combination of STATS19 accident records from Great Britain and the T1 accident records from Northern Ireland.

[3] The low HGV rate in Italy is surprising, and may be the result of the transformation rules used to import in the Italian data into the CARE database

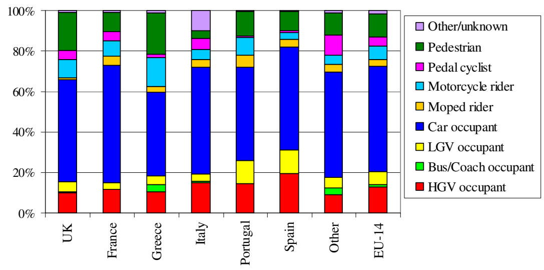

Figure 6. Distribution of fatalities in accidents involving HGVs in 2004, by road user type.

It can be seen that vulnerable road users, particularly pedestrians and motorcyclists account for a higher proportion of fatalities than in other EU countries with the exception of Greece.

Ranking of Casualty Groups

A total of 244 casualty groups were created and the number of casualties of each severity was identified for each group. The casualty groups were ranked based on the casualty count and the associated casualty costs for different casualty severities, fatal, KSI or all casualties.
Table 6 shows the ranking of casualty groups based on the count of KSI casualties and the annual cost of KSI casualties, with only the top ten shown as examples.

Table 6 shows that the ranking of casualty groups changes when both the severity and frequency of the casualties is considered. Some of the casualty groups appeared consistently in the top ten regardless of the criteria used for ranking, for example car occupants in impacts with an HGV or LCV. However these are both large groups and the impact configurations and injury mechanisms within these groups vary substantially. Pedestrians killed or seriously injured in impacts with HGVs, LPVs and LCVs all appear in the top ten when the groups were ranked by KSI cost. However, when ranked on KSI count, the pedestrians injured in impacts with HGVs are not in the top ten, whereas this group of casualties is the highest ranked of all the pedestrian casualties when based on cost. This indicates that the costs associated with the HGV-pedestrian casualties are higher even though there is a smaller number. In fact, the proportion of KSI pedestrians fatally injured in impacts with HGVs is higher than for the other two vehicle types, 33% for HGVs compared to 13% for both the LPVs and LCVs. Table 1 shows that the cost associated with a fatality is almost nine times that of the cost associated with a serious injury.

Table 6.

Examples of top ten KSI casualty groups ranked by count and annual cost

Rank	Accident Type	KSI Casualty Count	Accident Type	KSI Cost £M
1	Car Occupants in impact with HGV	2483	Car Occupants in impact with HGV	354.3
2	LCV Occupants	1983	Car Occupants in impact with LCV	195.4
3	Car Occupants in impact with LCV	1804	LCV Occupants	185.6
4	LPV Occupants	1351	Pedestrians in impact with HGV	136.1
5	HGV Occupants	1230	Pedestrians in impact with LPV	130.4
6	Pedestrians in impact with LPV	1204	HGV Occupants	127.5
7	LCV Occupants in impact with other vehicle	1173	Car Occupants in impact with HGV (Front – Front)	126.5
8	Pedestrians in impact with LCV	1121	Pedestrians in impact with LCV	121.7
9	LPV Occupants – no impact	875	LCV Occupants in impact with other vehicle	105.4
10	LPV Occupants – single vehicle	856	LPV Occupants	89.2

Detailed Accident Analysis

Detailed analysis was carried out on STATS19 data from 2003-2005. HVCIS fatal accident data covering the period 1997-2002 was also analysed. The analysis considered accidents involving HGVs, LCVs, LPVs, minibuses, OMVs and agricultural vehicles. Casualties that were the occupants of these vehicles or in opposition to these vehicles were included, which has resulted in too large an amount of data to report in this paper. Therefore, this paper presents the main findings of the detailed analysis of accidents that resulted in pedestrian impacts with the vehicles described above to provide an example of the types of analysis carried out.

STATS19 detailed analysis – The data sample consists of the numbers of pedestrian casualties as shown in Table 7 for impacts with each vehicle type.

Table 7.
Number of pedestrian casualties by impact with vehicle type in STATS 19 data sample, 2003-2005

Vehicle Type	Fatal	Serious	Slight	KSI
HGV	232	479	1314	711
LCV	146	975	3767	1121
LPV	156	1048	4583	1204
Minibus	6	86	349	92
Agricultural	4	21	57	25
OMV	19	163	821	182

Figure 7 summarises the vehicles that were in impacts with pedestrians that resulted in KSI casualties. The pedestrian casualties as a proportion of all KSI casualties for each vehicle type are also shown.

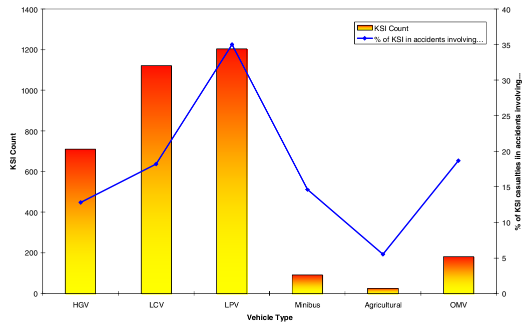

Figure 7. Number of pedestrian casualties with respect to impacting vehicle and as a percentage of all casualties from accidents involving this vehicle.

LPVs are the most frequent type of vehicle to be involved in a pedestrian impact with just over 1200 KSI casualties, an average of 401 per year. There are a similar number of pedestrian KSI casualties from impacts with LCVs. For HGVs, there is an average of 237 pedestrian KSI casualties per year. LPVs also have the highest proportion of pedestrian KSI casualties, with 35% of casualties from impacts with LPVs being pedestrians, compared to 18% for LCVs and 13% for HGVs. As a proportion of all KSI casualties, impacts with OMVs and minibuses are comparable to HGVs and LCVs, however there were a much lower number of casualties. The remainder of this analysis therefore focuses on the accidents involving LPVs, HGVs and LCVs.

STATS19 records the first point of impact for each vehicle. Where the first point of impact was known, the distributions by side of vehicle are summarised in Figure 8.

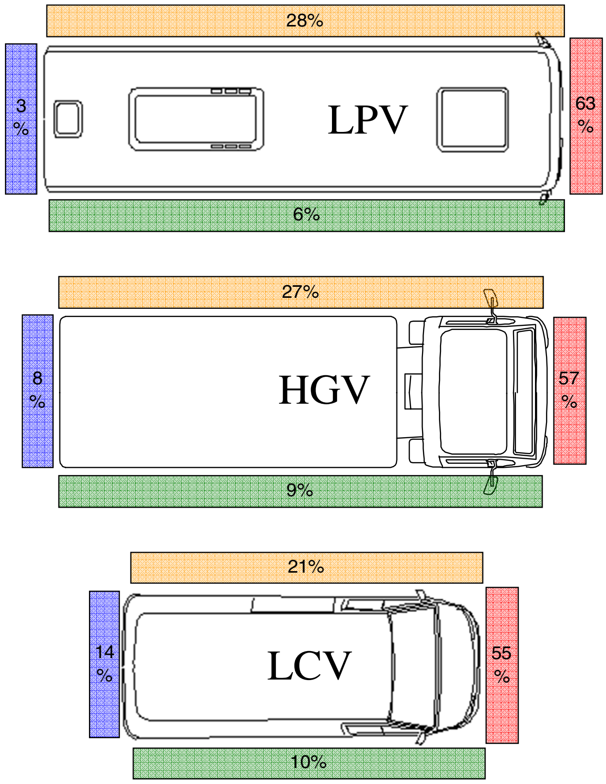

Figure 8. Impact locations for LPVs (top), HGVs (middle) and LCVs (bottom).

For all three vehicle types, most of the KSI casualties are injured in impacts with the front of the vehicle. The second most frequent impact area is the left side, which may be expected in a country where the vehicles are right hand drive because the left side is nearest to the footpath. Impacts to the rear of the vehicle are least frequent for the HGV and the LPV, however, impacts to rear of the LCV are third most frequent. The reasons for this are currently unknown.

At the time of the accidents that resulted in KSI casualties, most of the vehicles were described as "going ahead, other", 63% of LCVs, 65% of HGVs and 70% of LPVs. This category of manoeuvre is a very broad category which captures any vehicle that is not making a specific manoeuvre, and would therefore be expected to be the most frequent manoeuvre. The three most frequent vehicle manoeuvres for each vehicle are illustrated in Figure 9.

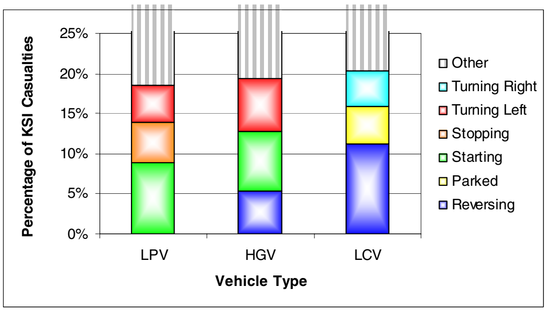

Figure 9. Three most frequent vehicle manoeuvres for KSI pedestrian causalities by vehicle type.

For LPVs the most frequent specific manoeuvre was the vehicle starting from rest, which was also the case for the HGVs. For LPVs this is possibly because many impacts occur as the vehicle is pulling away from a bus stop. For HGVs, the forward blind spot is often a contributory factor in these cases. For LCVs, starting was not one of the three most frequent manoeuvres. Turning left was also more common for LPVs and HGVs than it was for LCVs. This is related to the cut-in effect of the longer vehicles and this is also consistent with the left side of the vehicle being impacted. Stopping was only one of the three most frequent manoeuvres for the LPVs and this is possibly because these vehicles are frequently stopping at bus stops. Reversing was one of the more frequent manoeuvres for both of the goods vehicle categories with it being most frequent for the LCVs. Again, this is consistent with a higher proportion of impacts to the rear of this type of vehicle. For LCVs, turning right and being parked were two of the three most frequent manoeuvres, but these manoeuvres were not seen in the top three for HGVs and LPVs. Accidents where an LCV was parked include roadside assistance vehicles parked on the motorway hard should attending to a broken down vehicle where a second vehicle collides with the LCV pushing it into the LCV driver or the driver of the broken down vehicle who are no longer inside their vehicles. This different pattern may be related to the LCVs being more similar to passenger cars than the other two vehicle types.

If only the fatalities are considered, the most frequent manoeuvres remain the same, albeit with a higher proportion of the fatalities. For example, 71.2% of the HGVs were going ahead other and 8.6% were starting, compared with 64.8% and 7.4% for KSI pedestrian casualties. Also, going ahead on a left hand bend became one of the more frequent manoeuvres for LCVs and LPVs, accounting for 4.1% and 3.8% of fatalities respectively.

The location of the pedestrian at the time of the accident is shown in Figure 10.

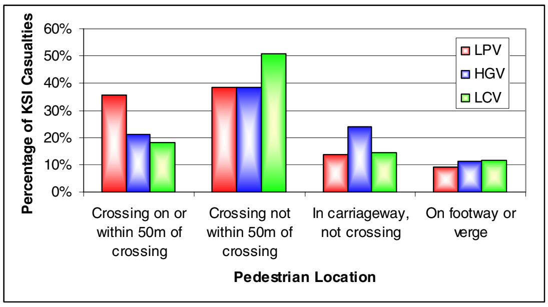

Figure 10. Pedestrian location at time of accident.

For all vehicle types, the majority of the pedestrians were injured while crossing the road. However, for pedestrians injured in impacts with LPVs, similar proportions were crossing on or near a crossing or elsewhere. For pedestrians injured by HGVs or LCVs, most were not on or near a crossing. For HGV impacts, the proportion of pedestrians that were in the carriageway, but not crossing was similar to the proportion that were on or near a crossing.

Figure 11 describes the movement of the pedestrian at the time of the impact.

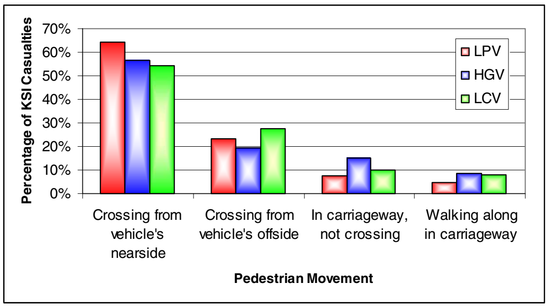

Figure 11. Pedestrian movement at time of accident.

For all three types of vehicle, most of the pedestrians were crossing the road from the vehicles nearside.

HVCIS fatals detailed analysis – The following analysis is based on final release of the HVCIS fatals phase 1 database (April 2006). This release of the HVCIS fatals database was compared with data from STATS19 for accidents involving each of the sample vehicle types to investigate the representativeness of the sample so that findings from analysis of the data can be used to estimate national trends. The database is broadly representative of the national data recorded by STATS 19. Accidents involving HGVs are the most representative, because they are the most numerous and form the largest sample. The data on LPVs is slightly less representative and analysis of accidents involving LCVs should be date restricted to for accidents prior to 1999 in order to avoid bias

(Knight *et al*, 2006), The following analysis of the LCV data has therefore been carried out using an earlier version of the phase 1 fatals database which contains the pilot study data to reduce the bias towards LCV impacts with other larger vehicles.

The data contained 173 pedestrians where the most severe impact was with an HGV, 116 that were impacted by an LPV and 59 pedestrians in impacts with LCVs. Figure 12 shows a comparison of the distribution of differences between impact locations. It is important to note that STATS19 records the first point of impact and the HVCIS data contains multiple impacts and is analysed using the most severe impact. This may explain some of the differences but pedestrian accidents are more likely to involve single impacts than multiple vehicle collisions.

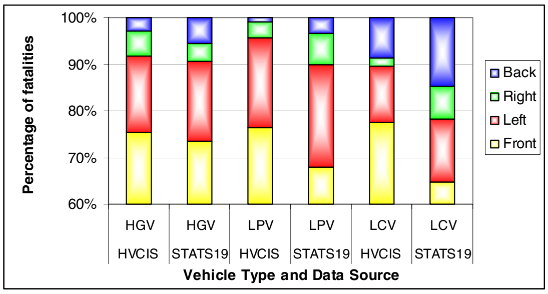

Figure 12. Comparison of impact locations between HVCIS and STATS19 by vehicle type[4].

Figure 12 shows that the representativeness of the data for accidents involving HGVs extends to the distribution of impact location. For LPVs and LCVs the data is less representative and when considering the following analysis, which considers impacts to the front of the vehicle, the data will be under-representing the national picture.

The HVCIS database contains data in addition to what is available from STATS19 such as:

- Driver behaviour factors
- Impact speed
- Cause of death
- More detail on impact location/sequence
- Fatality (pedestrian) behaviour factors

The following analysis compares some of this additional data for the three vehicle types LPV, HGV and LCV, focusing on impacts to the front of the HGV.

[4] The HVCIS data has an additional impact location of the underside of the vehicle. For the purpose of the comparison, the small number of impacts to the underside has been excluded as unknown. For LPVs and LCVs they account for 1.7% of fatalities and for HGVs 1.2%.

The impacts are coded using the direction of force, side and part components of the collision damage classification (CDC) (Nelson, 1980). Figure 13 summarises the impact locations on the front of the vehicles where this was known.

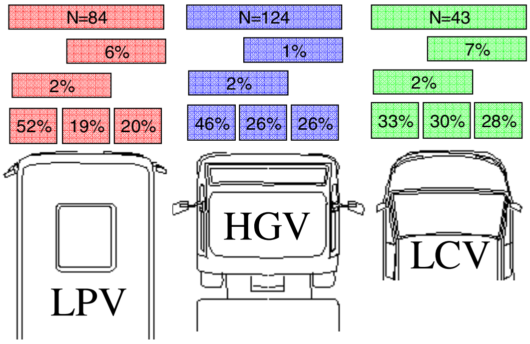

Figure 13. Pedestrian impact location on front of LPV (left), HGV (centre) and LCV (right).

The left side of the front of the vehicle is the most frequent impact location, which is to be expected for right hand drive vehicles because this is the side nearest to the footpath. The proportion of pedestrians in impacts with the front left of the vehicle varies by vehicle type. For LPVs and HGVs approximately 50% of the pedestrians impact the front left, whereas for LCVs the distribution of impact locations is more even. There are some cases where the impact is described as being distributed across two-thirds of the vehicle. In these cases, the exact impact location may not have been clear.

Data on impact speed is taken from witness statements, police calculations or from tachograph charts where they were analysed by the police. The data for impacts between the front of the vehicle and pedestrians is shown in Figure 14.

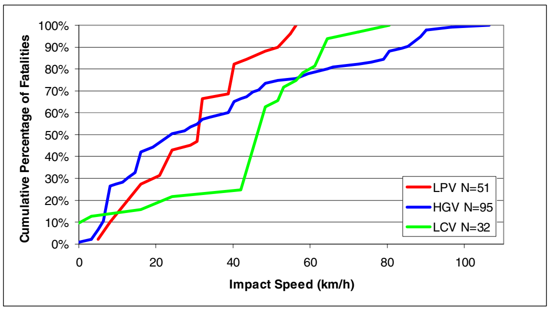

Figure 14. Cumulative percentage of impact speed by vehicle type.

The median impact speed is approximately 25km/h for HGVs, 30 km/h for LPVs and 45km/h for LCVs. Offering protection to pedestrian in impacts up to 40 km/h could protect up to 25% of those in impacts with LCVs, up to 65% of those in impacts with HGVs and up to 80% of those in impacts with

LPVs. However, when considering potential countermeasures, the primary impact with the vehicle may not always be the cause of the fatal injuries. For example the pedestrian could be run over or the secondary impact with the ground may be more severe than the impact with the vehicle.

For impacts with LCVs, 10% of the LCVs have a collision speed of zero which is consistent with frequency of parked LCVs involvement in accidents (Figure 9).

The cause of death is also an important factor when considering potential countermeasures. Figure 15 summarises the cause of death where the information was available.

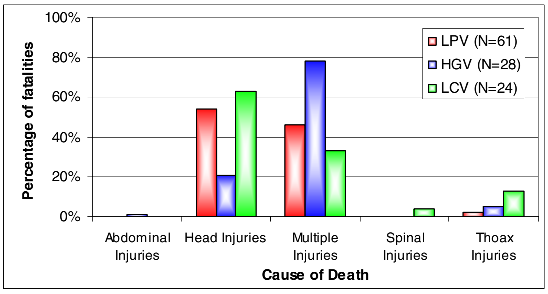

Figure 15. Cause of death for pedestrians in impacts with the front of LPVs, HGVs and LCVs.

For pedestrians in impacts with LPVs or LCVs, the most frequent cause of death in head injuries, however it is not possible to identify whether the injuries were caused by the impact with the vehicle or the impact with the ground. For pedestrians in collision with an HGV, multiple injuries is the most frequent cause of death, which suggests that collisions with HGVs are more severe than impacts with other vehicle types.

Data relating to body regions that sustain serious injury is also collected. The head was the most frequently injured body region. Where the seriously injured body regions were known, 90% of pedestrians in collision with an LPV, 71% of those in collision with an HGV and 83% of those in collision with an LCV sustained a serious injury to the head, either alone or in conjunction with other serious injuries. The head was the sole serious injury for 40%, 34% and 62% of those in collision with LPVs, HGVs and LCVs respectively.

Behavioural factors that were considered contributory to the cause of the accidents are recorded for both the driver and the fatality, which in this case is the pedestrian. Figure 16 shows the proportion of vehicle drivers and the pedestrians that were in collision with the vehicles, the actions of which were considered contributory to the accident. In some cases, the behaviour of both the driver and the pedestrian can be contributory to the cause of the accident and therefore the combined proportions can exceed 100%.

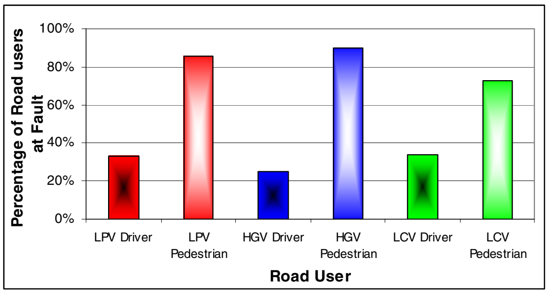

Figure 16. Road users whose behaviour was considered contributory to the accident.

In general, the pedestrians were considered to be at fault more frequently than the vehicle drivers. Lack of attention was considered to be the most frequent type of contributory behaviour for all the drivers and pedestrians. For the pedestrians, the most frequent behavioural factors were:

- Pedestrians in collision with LPV
  - 33% lack of attention
  - 18% alcohol alone or in conjunction with other behaviour
- Pedestrians in collision with HGV
  - 23% lack of attention only
  - 19% inconspicuous alone or in conjunction with other behaviour
  - 18% error of judgement only
  - 15% alcohol alone or in conjunction with other behaviour
- Pedestrians in collision with LCV
  - 42% lack of attention alone
  - 10% alcohol alone or in conjunction with other behaviour

It is necessary to mention that these behavioural factors are not mutually exclusive, for example a pedestrian that is affected by alcohol can sometimes not be paying attention or could make an error of judgement.

DISCUSSION

This paper has presented a summary and a few examples of the research to date. Analyses similar to those of the pedestrians have been carried out for other road users, car occupants, HGV occupants, pedal cyclist, motorcyclists, LPV occupants and others. The analyses will be used to determine parameters for potential countermeasures for some of the most frequently injured road user groups that are involved in accidents with large passenger, goods or agricultural vehicles. It is envisaged that a countermeasure may be effective for a number of road user groups.

The ranking spreadsheet will be used to focus the analysis of potential countermeasures on the larger casualty groups. However, some of the groups that appear high up in the rankings may have been the subject of recent legislation that could affect their position without any further intervention. For example, front underrun protection was recently introduced, however the market penetration has not been sufficient to influence the accident population yet and therefore the position of car occupants in impacts with the front of HGVs in the ranking spreadsheet is unaffected by this measure at this time. The feasibility of identifying a measure that is effective for protecting all car occupants in impacts with HGVs is low and so although top of the ranking spreadsheet, it may be more cost-effective to target some of the other casualty groups.

Smaller casualty groups will also be considered. For example, the number of agricultural vehicle occupant casualties is much lower than the number of pedestrians injured in impacts with HGVs, but the cost of introducing countermeasures may be lower either because of the technology or the smaller vehicle fleet.

CONCLUSIONS

The following conclusions can be drawn from the research to date:

- The literature review showed that most changes to regulations in the past have been supported by estimates of potential benefits and that the predictions have become more comprehensive with time.
- There has been minimal research to consider how effective previous changes to regulations have actually been.
- Analysis of the effect of introducing rear underrun protection systems show that those rigid vehicles that are exempt from the regulations are over-represented in impacts between the front of the car and the rear of the HGV which result in injury, thus suggesting it is an effective measure.
- Analysis of the contribution of accidents involving LPVs, HGVs and LCVs to meeting the UK casualty reduction targets showed that accidents involving HGVs and LCVs have made a contribution that is ahead of the average contribution for all accidents. Accidents involving LPVs have made a contribution that is below average.
- Consideration of the UK accident data within a European context showed that the fatality rate per million population is lower than for most European countries for accidents involving HGVs and LCVs, but is about average for accidents involving LPVs.
- Car occupants in an impact with an HGV were highlighted as the highest priority group of casualties based on both the casualty count and the societal costs associated with the casualties (which accounts for casualty severity). However, there have been recent changes to vehicle design (e.g. front underrun protection systems) that could deliver a significant reduction in this casualty group.
- The detailed analysis of STATS19 showed that the impact configurations for accidents resulting in pedestrian KSI casualties are similar for LPVs, HGVs and LCVs with the front and nearside being the most frequent impact locations. However, there were some differences between vehicle types when considering the manoeuvres that the vehicles were making at the time of the accident with "starting" and "turning left" two of the most frequent manoeuvres for LPVs and HGVs, but not for the LCVs.
- Analysis of impact speeds using the HVCIS fatals database showed that offering protection to pedestrians from LCVs, HGVs and LPVs at speeds up to 40 km/h could prevent up to 25%, 65% or 80% of the fatalities respectively.
- Pedestrian collisions with HGVs were more severe when compared to collisions with LPVs and LCVs. From STAT19, a higher proportion of the KSI casualties were fatally injured and from HVCIS, impact speeds were higher and the cause of death was more often multiple injuries.
- The HVCIS data also indicated that the behaviour of the pedestrians was more frequently contributory to the cause of the accident than the behaviour of the drivers of the vehicles.

FUTURE WORK

To date, this research project has identified the most frequently injured casualty groups for different types of accident. A range of countermeasures will be identified to reduce the frequency or severity of the casualties from accidents involving the vehicle types described in this paper.

The information from the ranking spreadsheet will be combined with the information collected during the literature review and the countermeasure assessments to identify priority areas for future research and effective safety countermeasures. The final project report is due for publication in late summer 2007.

ACKNOWLEGEMENTS

This paper uses accident data from the United Kingdom Heavy Vehicle Crash Injury Study (HVCIS), which is funded by the Department for Transport.

The HVCIS database is managed by the TRL Accident Research Group on behalf of the Department for Transport.

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MASS TRANSIT BUS-VEHICLE COMPATIBILITY EVALUATIONS DURING FRONTAL AND REAR COLLISIONS.

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United States
Paper Number 07-0477

ABSTRACT

Mass transportation systems and specifically bus systems are a key element of the national transportation network. Buses are one of the safest forms of transportation. Nonetheless, bus crashes resulting in occupant injuries and fatalities do occur. Therefore, crashworthiness research is a continuing effort. Using funding from the Federal Transit Administration, NIAR at Wichita State University is performing research to analyze and improve the crashworthiness of mass transit buses.

According to the Traffic Safety Facts reports from 1999-2003, an average of 40 fatalities and 18,430 injuries of bus occupants occurred per year. An average of 11 bus occupants per year are killed in two vehicle crashes while 162 occupants per year of other vehicles are killed. For this period of time an average of 12,000 bus occupants per year are injured in two vehicle crashes while 8,800 occupants per year of other vehicles are injured.

Vehicle compatibility is an issue that needs to be addressed in order to reduce the number of fatalities and injuries to mass transit bus, and collision partner vehicle occupants. Crash incompatibility between vehicles has been attributed to three factors: mass, stiffness, and geometric incompatibilities. The objective of this research is to identify vehicle compatibility issues encountered during typical Mass Transit Bus collisions with sedans, light trucks, and heavy trucks through the use of numerical finite element simulations. The findings of this research can be used in the future by bus and vehicle manufacturers to improve crash compatibility.

INTRODUCTION

Mass transportation systems and specifically bus systems are a key element of the national transportation network. According to data from the Nation Transportation Statistics 2005 report [1]; transit bus usage, in terms of passenger-miles, averages 20.6 billion miles per year. From 1992-2002, transit motor bus ridership has increased 11% in terms of unlinked trips. From 1990-2002, the number of transit motor buses in the U.S. has increased 30%. Clearly, transit buses are an integral part of the national transportation system. Buses are one of the safest forms of transportation. Nonetheless, bus crashes resulting in occupant injuries and fatalities do occur.

According to the Traffic Safety Facts reports from 1999-2003, an average of 40 fatalities and 18,430 injuries of bus occupants occurred per year. As shown in figure 1 and 2, an average of 11 bus occupants per year are killed in two vehicle crashes while 162 occupants per year of other vehicles are killed (102 occupants in passenger cars, 49 in light trucks, 9 in motorcycles, and 2 in large trucks).

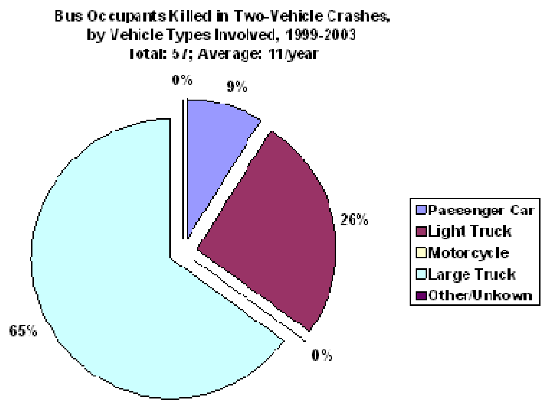


Figure 1. Bus Occupants Killed in Two-Vehicle Crashes, by Vehicle Types Involved.

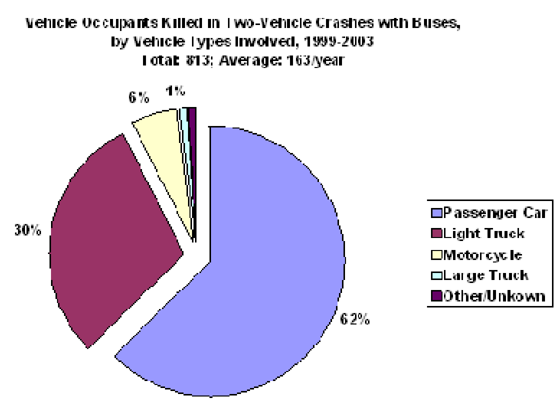


Figure 2. Vehicle Occupants Killed in Two-Vehicle Crashes with Buses, by Vehicle Types Involved.

An average of 12,000 bus occupants per year are injured in two vehicle crashes while 8,800 occupants per year of other vehicles are injured (6,000 in passenger cars and

2,800 in light trucks). Note that in the Traffic Safety Reports, buses are defined as “Large motor vehicles used to carry more than ten passengers, including school buses, inter-city buses, and transit buses”.

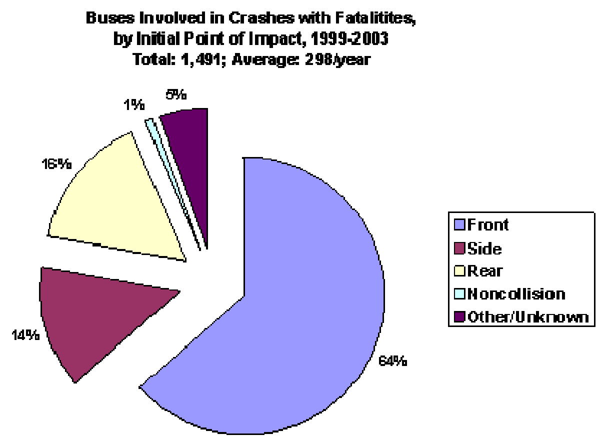


Figure 3. Buses Involved in Crashes with Fatalities, by Initial Point of Impact.

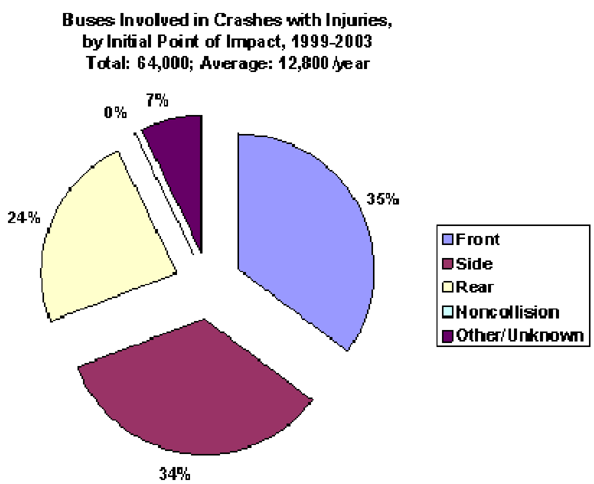


Figure 4. Buses Involved in Crashes with Injuries, by Initial Point of Impact.

According to the ‘Buses Involved in Fatal Accidents’ reports from 1999-2001, an average of 111 transit buses are involved in a fatal traffic accident each year. A total of 246 fatalities resulted from transit bus involvements from 1999-2000. Forty three percent of the fatalities were drivers of other vehicles, 37% were pedestrians, and 13% percent were passengers of other vehicles. The majority of transit bus fatalities occur during the work week, in urban environments, on dry roadway surfaces under normal weather conditions. Over half of fatal transit bus involvements occur on roadways with posted speed limits of 25-35 mph. Shorter, heavy-duty, low-floor transit buses account for the majority of fatal transit bus involvements. Eighty two percent of two vehicle fatal transit bus involvements on the same trafficway, same direction resulted from a rear-end, bus struck. Eighty eight percent of two vehicle fatal transit bus involvements on the same trafficway, different direction resulted from a head-on collision in the buses’ lane

In mass transit bus-to-vehicle crashes, two vehicle safety viewpoints have to be addressed:

- Self-protection, the ability of a vehicle to protect its own occupants.

- Partner-protection, the ability of a vehicle to protect the occupants of the partner vehicle.

Therefore compatibility should be defined as the ability of a vehicle to provide self- and partner-protection in a manner that optimum overall safety is achieved. It is generally accepted that compatibility should take place without compromising self-protection.

Vehicle compatibility is an issue that needs to be addressed in order to reduce the number of fatalities and injuries to mass transit bus, and collision partner vehicle occupants. Crash incompatibility between vehicles can be attributed to three vehicle factors: mass, stiffness, and geometric incompatibilities. The effect of vehicle mass is relatively straightforward. However, the influence of stiffness and geometric compatibility require additional research.

The objective of this research is to identify vehicle compatibility issues encountered during typical Mass Transit Bus collisions with sedans, light trucks, and heavy trucks through the use of numerical finite element simulations. The findings of this research can be used in the future by bus and vehicle manufacturers to improve crash compatibility.

ANALYSIS METHODOLOGY

For two vehicles colliding the conservation of momentum is defined as;

$$M_1 \cdot V_{1i} + M_2 \cdot V_{2i} = M_1 \cdot V_{1f} + M_2 \cdot V_{2f}$$

the coefficient of restitution is defined as the ratio of velocities pre- and post-crash;

$$C_r = \frac{V_{2f} - V_{1f}}{V_{1i} - V_{2i}}$$

By solving the system of equations above, the residual velocities of a two vehicle collision upon impact are;

$$V_{1f} = \frac{[(C_r + 1) \cdot M_2 \cdot V_{2i}] + [V_{1i} \cdot [M_1 - (C_r \cdot M_2)]]}{M_1 + M_2}$$

$$V_{2f} = \frac{[(C_r + 1)\cdot M_1 \cdot V_{1i}] + [V_{2i} \cdot [M_2 - (C_r \cdot M_1)]]}{M_1 + M_2}$$

The energy dissipated by the vehicles structure upon impact is defined by the difference in kinetic energy pre and post-crash;

$$E_d = \frac{1}{2}\cdot\left(M_1 \cdot V_{1i}^{\;2} + M_2 \cdot V_{2i}^{\;2}\right) - \frac{1}{2}\cdot\left(M_1 \cdot V_{1f}^{\;2} + M_2 \cdot V_{2f}^{\;2}\right) \quad \text{(EQ 1)}$$

by substituting the residual velocities in the equation above, the energy dissipation equation becomes;

$$E_d = \frac{1}{2}\cdot\left(M_1 \cdot V_{1i}^{\;2} + M_2 \cdot V_{2i}^{\;2}\right) - \frac{1}{2}\cdot \left(M_1 \cdot \left[\frac{[(C_r+1)\cdot M_2 \cdot V_{2i}] + [V_{1i}\cdot[M_1 - (C_r \cdot M_2)]]}{M_1 + M_2}\right]^2 + M_2 \cdot \left[\frac{[(C_r+1)\cdot M_1 \cdot V_{1i}] + [V_{2i}\cdot[M_2 - (C_r \cdot M_1)]]}{M_1 + M_2}\right]^2 \right)$$

for Mass Transit Bus to Vehicle frontal collisions we can assume that the coefficient of restitution is approximately zero, hence the energy dissipation equation becomes;

$$E_d = -\frac{1}{2}\cdot M_1 \cdot M_2 \cdot \frac{V_{1i}^{\;2} + V_{2i}^{\;2} - 2\cdot V_{2i}\cdot V_{1i}}{M_1 + M_2} \quad \text{(EQ 2)}$$

The equation above (EQ 2) can be used to predict the amount of energy absorbed by both vehicles during impact, given that the masses and initial velocities are known. If initial and final velocities are known then equation 1 should be used.

Another method to find the total energy dissipated during impact can be calculated when the vehicle stiffness's and crush values are known;

$$E_d = \int_0^{X_{c1}} F(x)_1 \cdot dx_1 + \int_0^{X_{c2}} F(x)_2 \cdot dx_2 \quad \text{(EQ 3)}$$

If we assume a linear behavior for the vehicle stiffness equation 3 becomes;

$$E_d = \frac{1}{2}\cdot K_1 \cdot Xc_1^{\;2} + \frac{1}{2}\cdot K_2 \cdot Xc_2^{\;2} \quad \text{(EQ 4)}$$

In order to find the crush distance of the partner vehicle we can combine equations two and four into the following expression (EQ 5):

$$X_{c1} = \frac{1}{K_1}\cdot\left[-K_1 \frac{\left(\begin{array}{l} -M_1 \cdot M_2 \cdot V_{1i}^{\;2} - M_1 \cdot M_2 \cdot V_{1i}^{\;2} \\ +2\cdot M_1 \cdot M_2 \cdot (-V_{1i})\cdot V_{1i} \\ +K_2 \cdot X_{c2}^{\;2}\cdot M_1 + K_2 \cdot X_{c2}^{\;2} \cdot M_2 \end{array}\right)}{M_1 + M_2}\right]^{\frac{1}{2}}$$

Where;

C_r, Coefficient of Restitution

E_d, Energy Dissipation

F_b, Structural Force, Bus

F_v, Structural Force, Partner Vehicle

K_1, Linear Stiffness, Partner Vehicle

K_2, Linear Stiffness, Bus

M_1, Mass, Partner Vehicle

M_2, Mass, Bus

V_{1f}, Final Impact Velocity, Partner Vehicle

V_{1i}, Initial Impact Velocity, Partner Vehicle

V_{2f}, Final Impact Velocity, Bus

V_{2i}, Initial Impact Velocity, Bus

X_{C1}, Crush Distance, Partner Vehicle

X_{C2}, Crush Distance, Bus

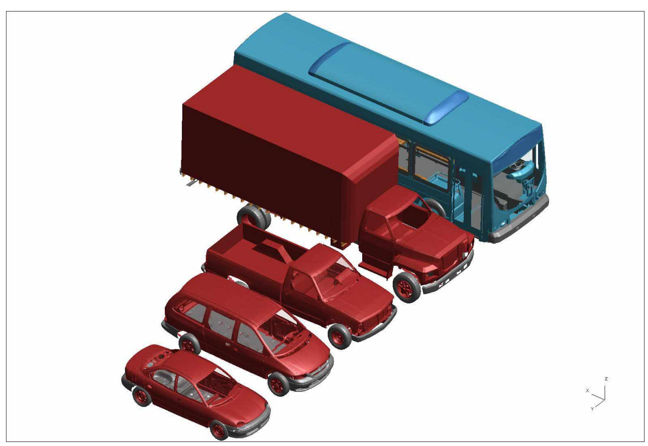


Figure 5. Finite Element Model Vehicles.

Overview Vehicle Numerical Models Databases

Numerical models were used to conduct this compatibility study. The low floor mass transit bus model has been validated for frontal, rear, side and rollover impact conditions (for more detailed model information refer to reference 4). The Dodge Caravan and Neon finite element models have been validated for frontal and offset impact conditions (for more detailed model information see reference 5). Although there is no validation report available for the F800 and C2500 finite element models, these models where used to evaluate the mass transit bus performance. Table one provides an overview of the vehicles weight.

Accelerometers in the area of the lower B-pillar were selected for the analysis, see figure 6 for the location in the mass transit bus, and figure 7 for the location in the collision partner.

Table 1.

Vehicles mass overview

Vehicle	Mass (kg)	Mass Ratio
Bus	10360	1
F800	7792	0.75
Caravan	2043	0.19
C2500	1813	0.175
Neon	1333	0.13

Table 2.

Vehicle stiffness overview calculated from 30 mph rigid barrier tests

	Linear Stiffness	Mass	Maximum Disp.
Bus*	5176	10360	0.6
Neon**	708.7	1354	0.686
Caravan**	904.2	2003	0.757
	kN/m	Kg	m

*** Based on simulation results. ** Based on NHTSA Tests [6].**

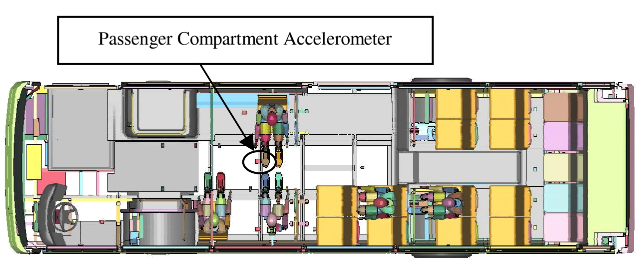


Figure 6. Transit Bus Accelerometer Location.

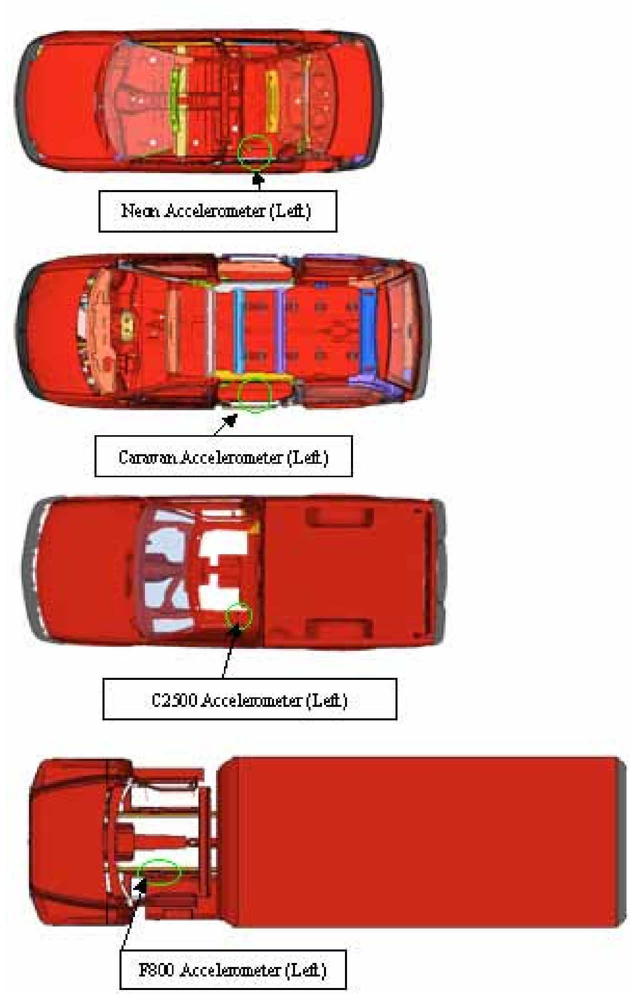


Figure 7. Collision Partner Accelerometer Locations.

SUMMARY SIMULATION RESULTS

Based on the data collected from typical mass transit bus accidents [7], the following frontal and rear impact conditions were analyzed

Table 3.

Summary impact conditions

Case	Impact Condition
1	Frontal: Bus - 30 mph (48.3 kph) : F800 – 30 mph
2	Frontal: Bus - 30 mph : Dodge Caravan - 30 mph
3	Frontal: Bus - 30 mph : Dodge Neon - 30 mph
4	Rear: Bus - 0 mph : Bus – 20 mph (32.2 kph)
5	Rear: Bus - 0 mph : Dodge Caravan - 20 mph
6	Rear: Bus - 0 mph : Dodge Neon - 20 mph
7	Rear: Bus - 0 mph : Chevy 2500 C - 20 mph

8	Rear: Bus - 0 mph : Bus - 20mph

<u>Frontal Impact Simulation Results</u>

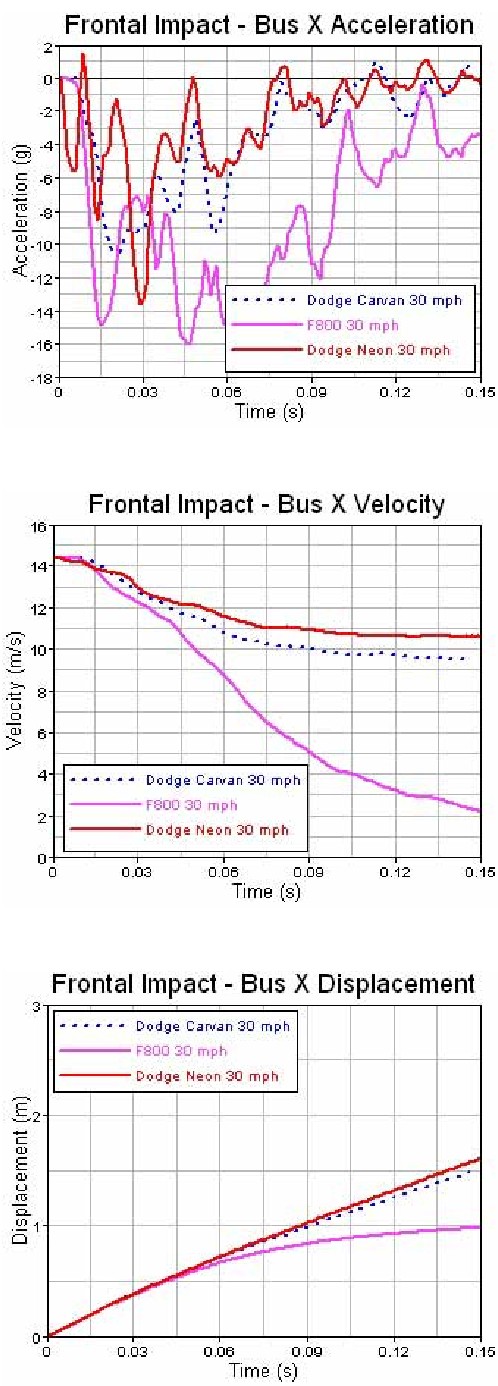


Figure 8. Mass Transit Bus Passenger Compartment Acceleration Velocity and Displacement.

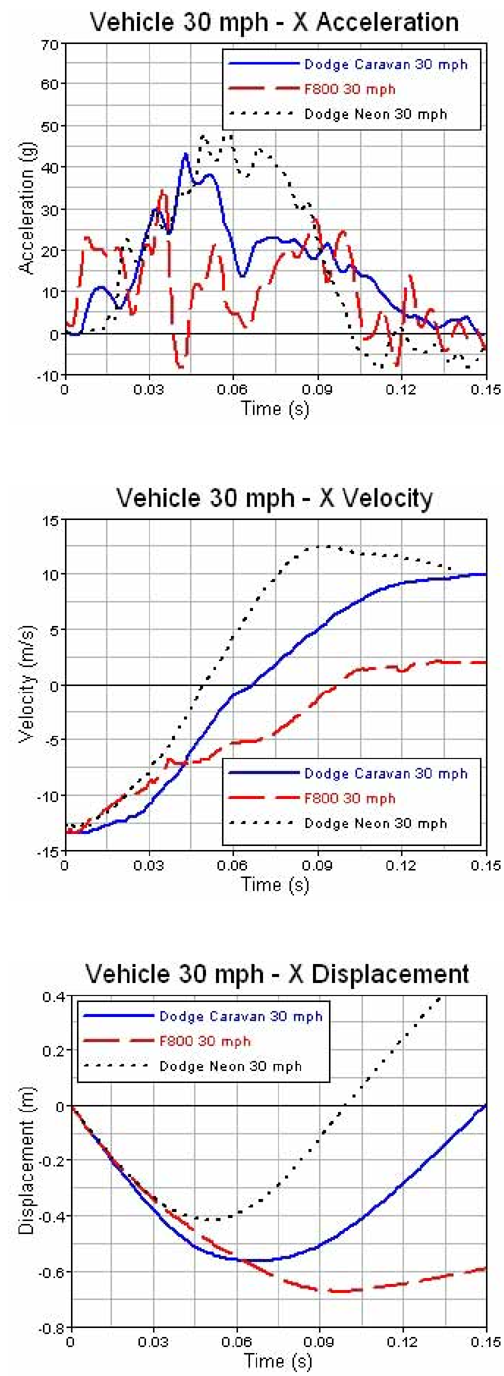


Figure 9. Partner Vehicle B-Pillar Acceleration, Velocity and Displacement.

Rear Impact Simulation Results

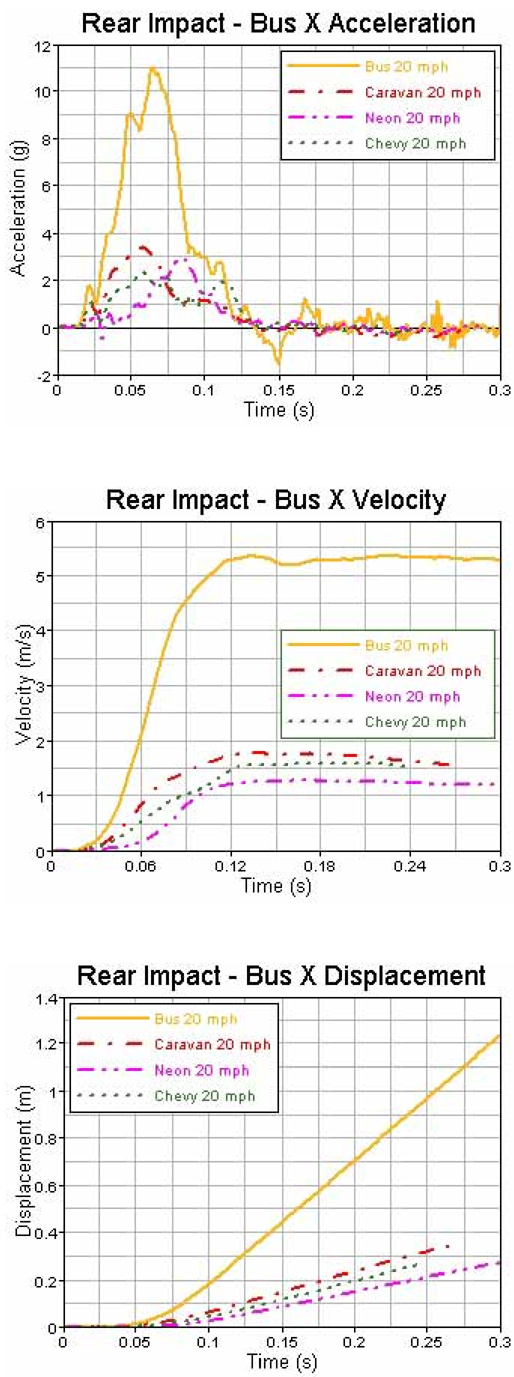


Figure 10. Mass Transit Bus Passenger Compartment Acceleration Velocity and Displacement.

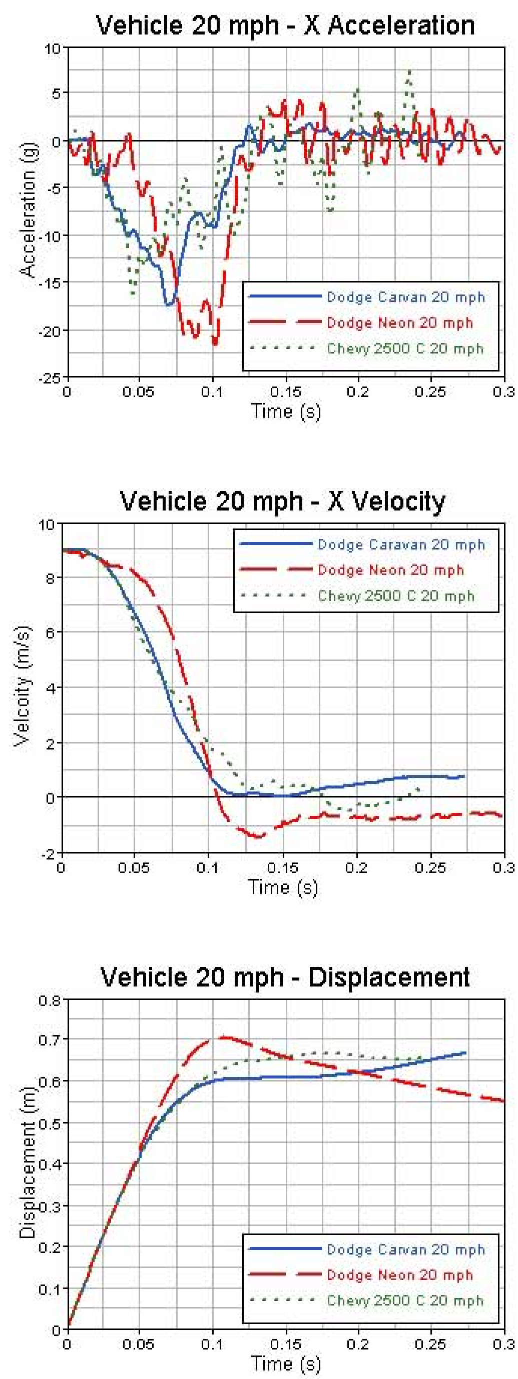


Figure 11. Partner Vehicle B-Pillar Acceleration, Velocity and Displacement.

GEOMETRIC COMPATIBILITY

Bus underbody clearance is defined in SAE J698 standard. This standard specifies the minimum clearance regardless of load up to the gross vehicle weight rating. As shown in figure 12 the approach angle shall be no less than 8 degrees, the departure angle shall be no less than 9 degrees, and the ground clearance shall be no less than 8.5 inches (216 mm) except within the axel zone and wheel area [8].

Bumpers shall provide impact protection for the front and rear of the bus with the top of the bumper being 26 ± 2 inches (660 ± 51 mm) above the ground. The front bumper system must comply with the following impact conditions defined in the Standard Bus Procurement Guidelines [8]:

- No part of the bus, including the bumper, shall be damaged as a result of a 5-mph (8 kph) impact of the bus at curb weight with a fixed, flat barrier perpendicular to the bus' longitudinal centerline.
- The bumper shall protect the bus from damage as a result of 6.5 mph (10.5 kph) impacts at any point by the Common Carriage with Contoured Impact Surface defined in FMVSS 301 loaded to 4,000 pounds (1814 kg) parallel to the longitudinal centerline of the bus and 5.5-mph (8.9 kph) impacts into the corners at a 30 degree angle to the longitudinal centerline of the bus.

The rear bumper system must comply with the following impact conditions defined in the Standard Bus Procurement Guidelines [8]:

- No part of the bus, including the bumper, shall be damaged as a result of a 2-mph (3.2 kph) impact with a fixed, flat barrier perpendicular to the longitudinal centerline of the bus.
- The rear bumper shall protect the bus, when impacted anywhere along its width by the Common Carriage with Contoured Impact Surface defined in Figure 2 of FMVSS 301 loaded to 4,000 pounds (1814 kg), at 4 mph (6.4 kph) parallel to, or up to a 30 degree angle to, the longitudinal centerline of the bus.
- The rear bumper shall be shaped to preclude unauthorized riders standing on the bumper.

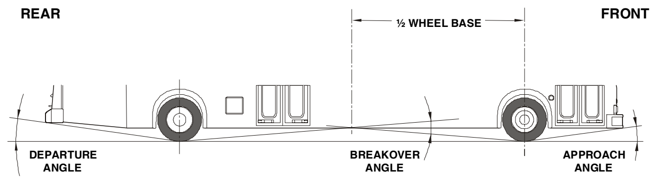


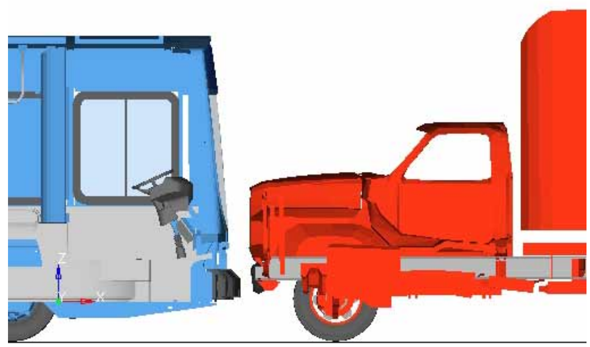
Figure 12. Transit Bus Diagram [8].

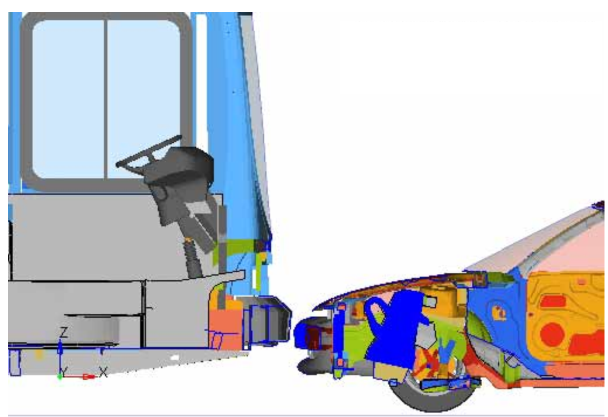
<u>Frontal Impact 30 mph 100 % Overlap</u>

According to data presented collected by the IHRA working group, typical frontal longitudinal member heights for sedans are in the range of 380/500 mm, and for SUV/Trucks in the range of 440/550 mm.

A shown in figures 13 through 16 the mass transit bus bumper system aligns with the frontal structural elements of the Dodge Neon and Caravan. There is a height mismatch between the bus and the F800; this could be prevented by increasing the height of the bus bumper or by equipping heavy trucks with under-ride devices.

Current Mass Transit Bus frontal bumper design standards provide the required data to design geometrically compatible frontal bumper systems with the majority of road vehicles.





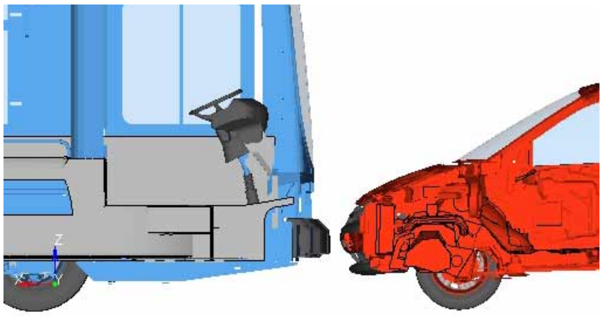
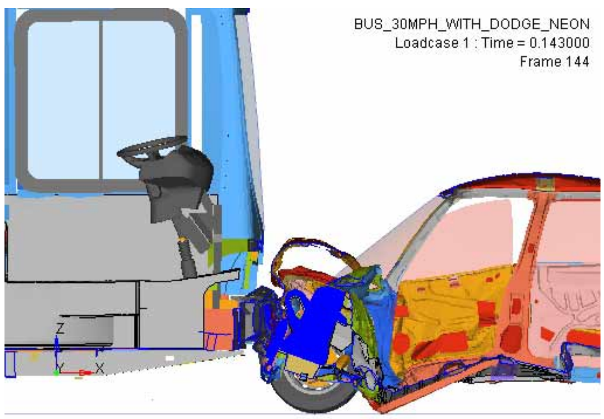
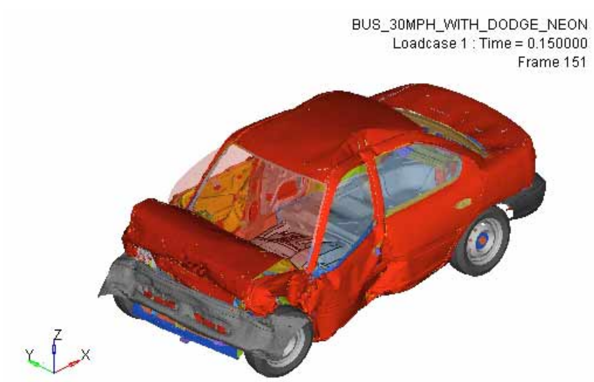
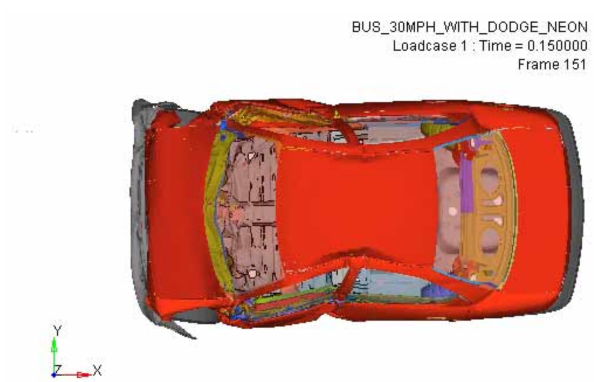


Figure 13. Frontal Impact Geometric Compatibility.







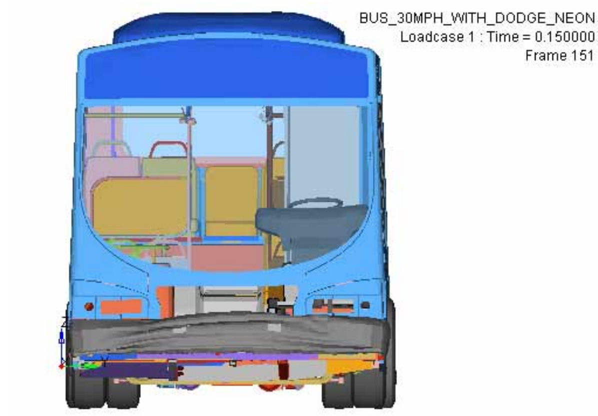
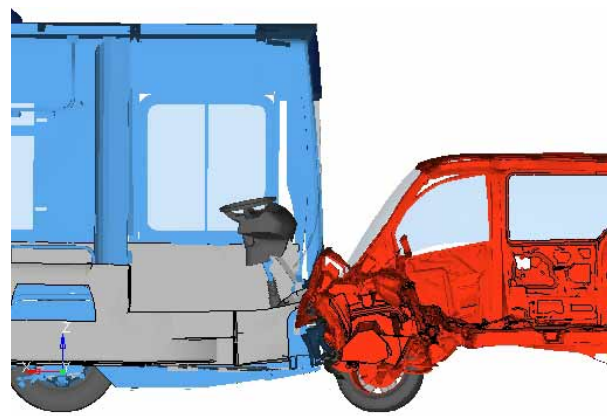
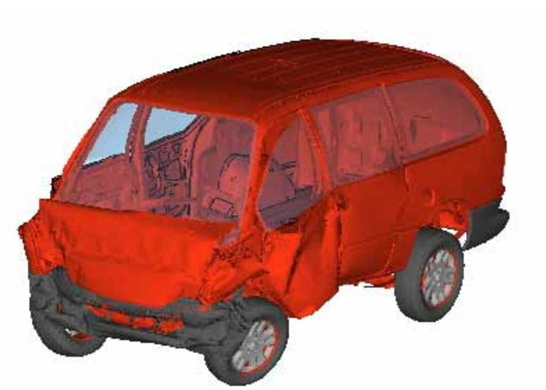


Figure14. Neon-Transit Bus Interaction.





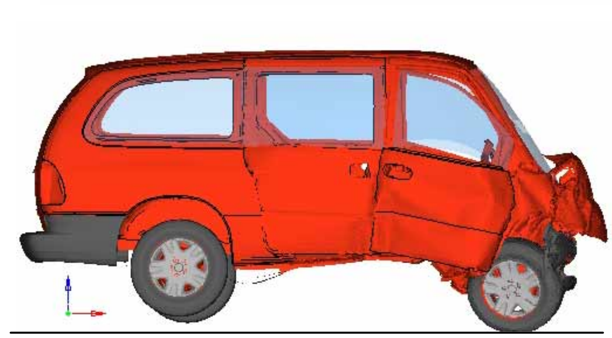


Figure15. Caravan-Transit Bus Interaction.

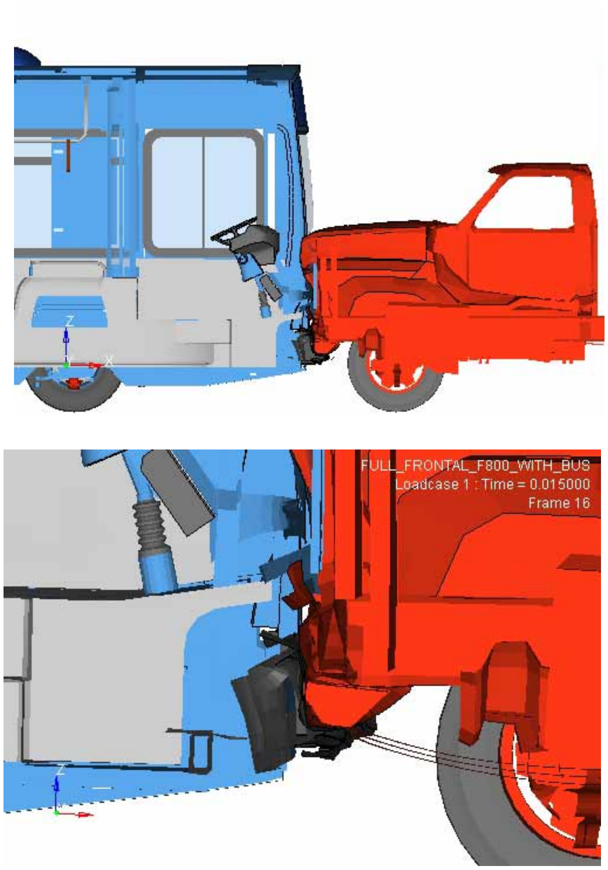


Figure16. F800 -Transit Bus Interaction.

__Rear Impact 20 mph 100% Overlap__

According to data obtained from “Mass Transit Crashworthiness Statistical Data Analysis” [7], the majority of rear impacts tend to occur at velocities bellow 30 mph (48.3 kph).

A shown in figures 17 through 19 the mass transit bus bumper system aligns with the frontal structural elements of the Dodge Caravan, C2500, and bullet mass transit bus. There is a height mismatch between the bus and the Dodge Neon; this could be prevented by lowering the height of the bus rear bumper system. Even though there is a height mismatch between the Neon and the transit bus the deceleration levels experience by the Dodge Neon are well bellow the 30 g deceleration threshold.

Current mass transit bus frontal bumper design standards provide the required data to design geometrically compatible bumper systems with the majority of road vehicles.

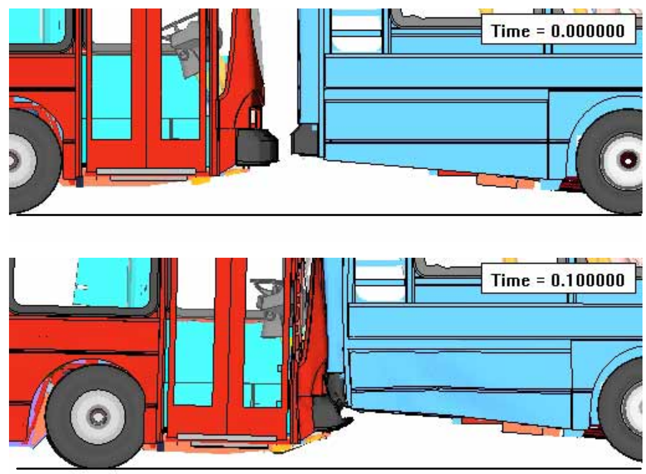


Figure 17. Bus 20 to Stationary Transit Bus.

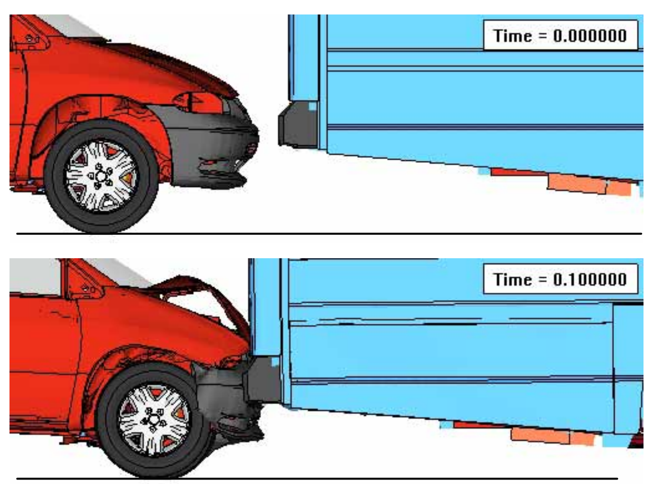


Figure 18. Caravan 20 mph to Stationary Transit Bus.

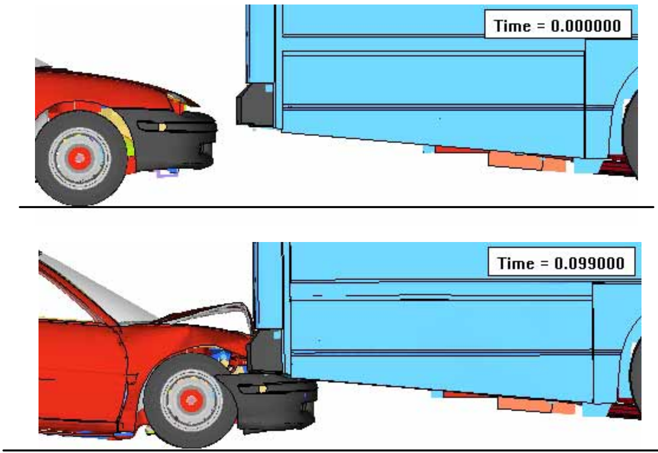


Figure 19. Neon 20 mph to Stationary Transit Bus.

MASS COMPATIBILITY

The conservation of momentum in a collision places smaller vehicles at a fundamental disadvantage when the collision partner is a heavier vehicle. As shown in table 1, there is a large difference in mass between the transit bus and the Dodge Neon/Caravan. Figure twenty illustrates the different range of energy absorbing specifications for the vehicles in this study versus the mass of the collision partner by using the equation derived in the previous section.

$$E_d = -\frac{1}{2} \cdot M_1 \cdot M_2 \cdot \frac{V_{1i}^2 + V_{2i}^2 - 2 \cdot V_{2i} \cdot V_{1i}}{M_1 + M_2}$$

Transit buses should be designed to absorb with its partner vehicle energy levels ranging from 424 kJ (impact with a small vehicle of mass 1333 kg) to 2000 kJ (impact with a large vehicle of mass 12000 kg). Compact vehicles such as the Dodge Neon will experience with its partner vehicle energy levels ranging from 239 kJ to 432 kJ (impact with a large vehicle of mass 12000 kg).

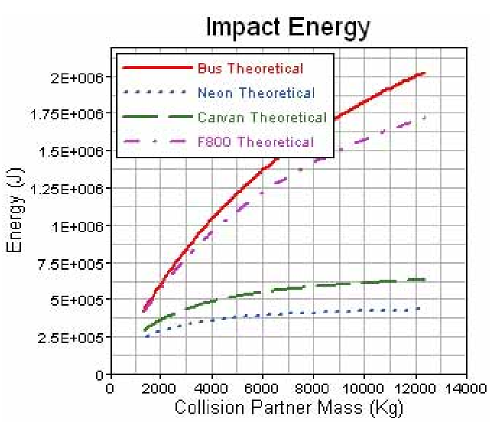


Figure 20. Crash Energy Dissipation vs. Collision Partner Mass for a 30 mph Frontal Collision.

The energy dissipated by the vehicles structure upon impact is defined by the difference in kinetic energy pre and post-crash. By applying the residual velocity values calculated with the finite element simulations (see figures 8 and 9) we can calculate the energy dissipation with the following equation;

$$E_d = \frac{1}{2} \cdot \left(M_1 \cdot V_{1i}^2 + M_2 \cdot V_{2i}^2 \right) - \frac{1}{2} \cdot \left(M_1 \cdot V_{1f}^2 + M_2 \cdot V_{2f}^2 \right)$$

The results of the Neon, Caravan, and F800 are plotted against the energy level prediction calculated with equation 2. Note that equation 2 can be used without prior knowledge of the residual velocities, see figure 21.

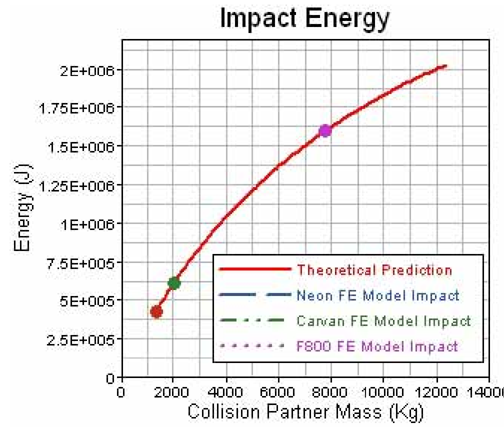
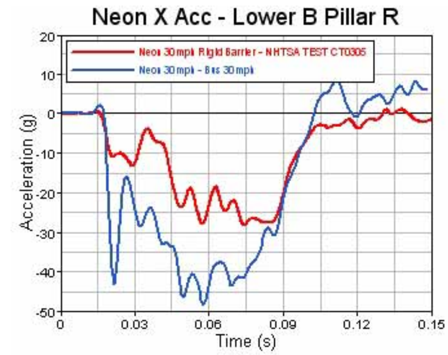


Figure 21. Crash Energy Dissipation Theoretical Prediction vs. Finite Element Model Results for a 30 mph Collision with a Transit Bus.

Other parameter influenced by mass is stiffness as shown in table 2. Variability in linear stiffness is directly proportional to the change in mass. For large mass differentials such as the Bus/Neon or Bus/Caravan the partner vehicle decelerates from impact velocity down to zero within the first 60 ms, afterwards it is accelerated to the residual velocity of the bus (See figures 22 and 23).



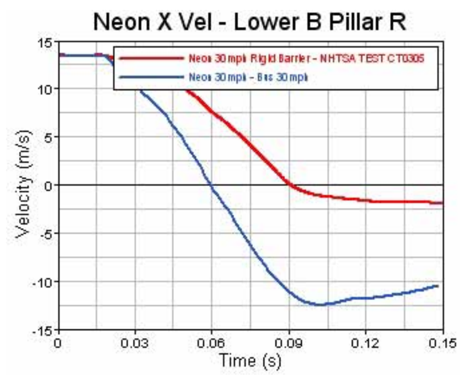
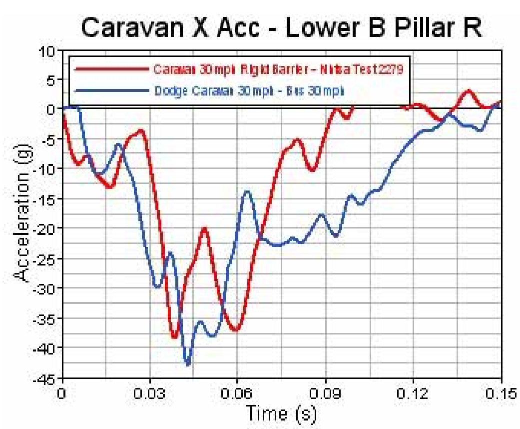


Figure 22. Dodge Neon Acceleration and Velocity at Lower B-Pillar Accelerometer Location, Comparison 30 mph Bus Impact vs. Rigid Barrier 30 mph NHTSA Test.



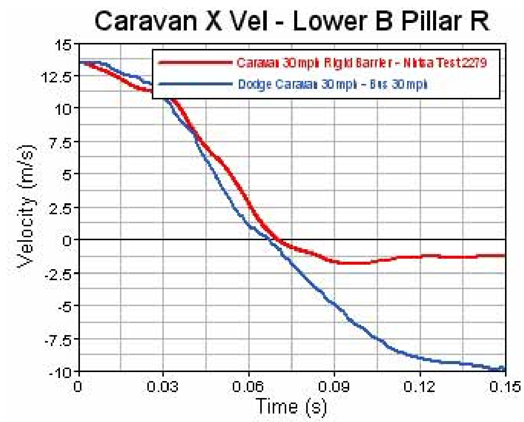


Figure 23. Dodge Caravan Acceleration and Velocity at Lower B-Pillar Accelerometer Location, Comparison 30 mph Bus Impact vs. Rigid Barrier 30 mph NHTSA Test.

STRUCTURAL STIFFNESS COMPATIBILITY

In the frontal collisions analyzed in this study, the vehicle with the lower stiffness (i.e. Caravan, and Neon) absorbs the bulk of the crash energy. For example in the 30 mph impact between the transit bus and the Dodge Caravan; the bus structure absorbs 108 kJ (18 %) while the Dodge Caravan structure absorbs 505 kJ (82 %). This results in large deformations of the partner vehicles as shown in figure 14, 15, 24, and 25. These large deformations in the partner vehicle can increase the injury potential for their drivers, and passengers.

In order to improve vehicle compatibility both vehicles need to dissipate equal levels of energy. Since mass is a fixed parameter, improvement can only be achieved by increasing the bus crush distance under load.

Due to the current transit bus design constraints, it may be difficult to increase the vehicle deformation to the desired levels without implementing variable stiffness active bumper systems triggered by pre crash sensors.

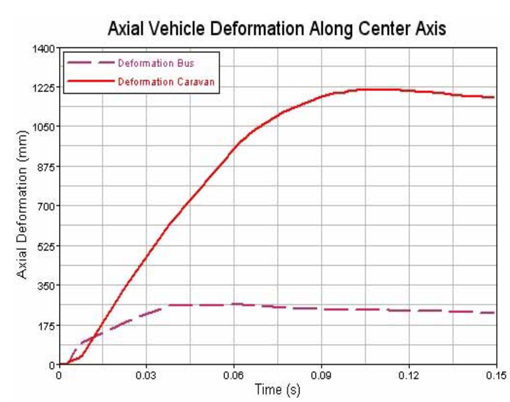


Figure 24. Mass Transit Bus and Caravan Change in Length, FE Simulation Results.

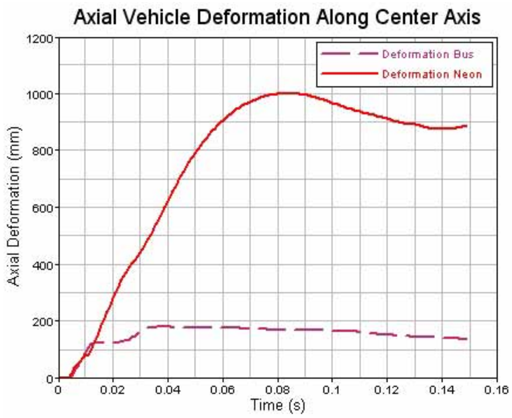


Figure 25. Mass Transit Bus and Neon Change in Length, FE Simulation Results.

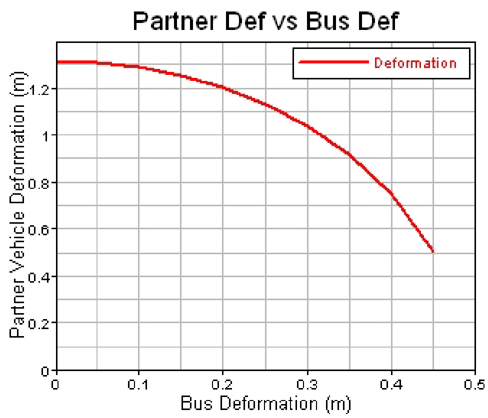


Figure 26. Calculated Increase in Bus Deformation vs. Decrease Dodge Caravan Deformation.

CONCLUSION

Buses are one of the safest forms of transportation. Nonetheless, bus crashes resulting in occupant injuries and fatalities do occur.

The results of this study show that current transit bus bumper geometry design guidelines [8] generate bumper designs that are compatible from a geometric point of view with most vehicles on the road today. The only issue may be insufficient height to improve its compatibility with lager trucks; in fact according to the Traffic Safety Facts statistics from 1999 to 2003 most of the occupant fatalities occur when the bus impacts a large truck (see figure 1).

In order to improve vehicle compatibility both vehicles need to dissipate equal levels of energy. Since mass is a fixed parameter, improvement can only be achieved by increasing the bus deformation under load. Due to the current transit bus design constraints, it may be difficult to increase the bus structural deformation to the desired levels without implementing variable stiffness active bumper systems triggered by pre crash sensors.

ACKNOWLEDGEMENTS

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AN ERGONOMICS EVALUATION OF THE SAFETY IMPACT OF A NEW ON-BOARD SYSTEM: SAFEMAP

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ABSTRACT

The SafeMap project, which is part of the DEUFRAKO programme (a cooperation between France and Germany), aims at assessing the use of a dedicated digital map for road safety applications. The consortium includes car and trucks manufacturers, map providers, universities, and other research agencies. The objectives are to define the database content in regards to safety, benefits, and data provision costs, to assess the feasibility of map data provision, to optimize the data provision chain (public authorities and private companies contributions), to provide a demonstrator with this system embedded, to evaluate in-vehicle safety applications using digital maps and driver acceptability.
Based on criteria of safety effectiveness and ease of implementation/deployment, Volvo has developed the following four functions for trucks:
(A) *Speed Limit Assistant,*
(B) *Curve Speed Warning,*
(C) *Frequent Accident Spot Warning,*
(D) *Physical restrictions warning*.
The aims of the present study were to assess the impact of information/warnings on driving, and to evaluate the acceptability of the SafeMap system as implemented by Volvo on an instrumented truck.

INTRODUCTION

Advanced Driver Assistance Systems (ADASs) have been developed to meet two major objectives; “to improve driver comfort in the face of increased driving demands, and to improve safety by reducing the hazards arising from driver under-performance” [1]. Research conducted in this field has demonstrated that the implementation of many ADAS could be substantially simplified when introducing digital maps, like those used by navigation systems, yet featuring expanded content. Using this statement as a basis, several research projects have investigated the technical feasibility of such enhanced digital mapping. In Europe, the Nextmap consortium [6] has completed a two-year project funded by the European Union (EC/DG XIII) and results have shown that enhanced map databases, coupled with accurate descriptions of road geometry plus additional content (e.g. road lanes, speed limits, traffic regulations), are technically feasible and enable generating various map-based vehicle applications that provide support for the driving task under both safe and comfortable conditions.

The SafeMap project [2], which is part of the DEUFRAKO program (a cooperation programme between France and Germany, which supports cross-national network activities, funds joint projects and launches joint calls for proposals), aims at assessing the use of a dedicated digital map for road safety applications. The consortium includes car and trucks manufacturers (Daimler Chrysler, PSA Peugeot Citroën, Volvo 3P/Renault Trucks), Map providers (TeleAtlas, Navteq), Universities and other research agencies (LCPC, Univ. Paris 5, Bast, ISIS…). More precisely, the objectives are to define the database content in regards to safety, benefits and data provision costs, to assess the feasibility of map data provision, to optimize the data provision chain (public authorities and private companies contributions), to provide a demonstrator with this system embedded and to evaluate in-vehicle safety applications using digital maps.
According to the two criteria of safety effectiveness and ease of implementation/deployment, the SafeMap consortium has been conducting assessments of the six following functions:

(A) *Speed Limit Assistant:* This function is similar to the various systems studied during the series of Intelligent Speed Adaptation initiatives across Europe. The legal speed limit information should cover the entire rural road network as well.
(B) *Frequent Accident Spot Warning:* Whenever current driving conditions correspond with a combination of accident circumstances that have already been produced on a given road section, a warning is delivered to the driver.
(C) *Overtaking Assistant:* This function warns the driver whenever an intended maneuver to overtake another vehicle is either prohibited or risky.
(D) *Hazardous Area Identification:* Identification of dangerous curves and junctions based on road characteristics.
(E) *Intersection Approach Speed Warning:* The appropriate speed for approaching an intersection is computed onboard, based on both map data and the particular driving situation.
(F) *Curve Speed Warning:* Safe speed when negotiating a curve is computed from map data, which takes into account road characteristics, vehicle dynamics and driver behavior.

Although safety benefit estimates of ADAS have been the focus of a large body of literature over the past ten years [i.e., 7], little human factors-based research on drivers' behavior or safety impact of ADAS systems has been conducted. A few published studies indicated, for example, that alarm systems help direct driver attention to safety traffic conditions [3; 8]. Other studies found that collision-warning systems helped drivers to estimate headway more accurately and, consequently, drivers maintained longer and safer headways [4]. But these are only a few.
The aims of the present study were to assess the impact of warnings on speed and to evaluate the acceptability of the SafeMap warnings as implemented by Volvo 3P/Renault Trucks:
(A) *Speed Limit Warning,*
(B) *Curve Speed Warning,*
(C) *Frequent Accident Spot Warning,*
(D) *Physical restrictions warning*.

METHOD

Participants

Participants were 14 licensed drivers (men) ranging in age from 36 to 57 years old (M = 51,0; SD = 6,0). Drivers were trucks test drivers and were recruited on a voluntary basis. They were all experienced with Renault trucks. Since the drivers could not be allocated to one of two groups *a priori* on the basis of their characteristics, they were allocated as a function of their order of participation (see Table 1).

Table 1.
Type of drivers by group

Profession	*Gr. 1*	*Gr. 2*
Mechanic test drivers	4	2
Technician test drivers	2	4
Adjusters test drivers	1	1
Total	7	7

The two groups differ statistically in terms of age (t (13) = -2,49; p = 0,03). The mean age was 47,5 years old (SD = 6,4; *range* = 36-55) for the participants in group 1 and 54,5 years old (SD = 2,6; *range* = 49-57) for the participants in group 2.
No statistical difference was observe between groups in terms of number of years of heavy weight truck driving (t (13) = -0,52; p = 0,62). Participants had 25 (SD = 9,1) and 28 (SD = 10,6) years of experience in group 1 and 2 respectively.
Most of the drivers used to drive everyday (Table 2). The two groups were not statistically different on this aspect (χ^2 (1; N = 14) = 0,00; $p > 0,05$) but differ in terms on number of kilometers participants covered in the past twelve months (χ^2 (1; N = 14) = 4,98; $p <$ 0,05) (Table 3). Participants in group 1 traveled more kilometers than the participants in group 2. Only 1 driver was used to use a GPS and none of the participants use an in-vehicle information system.

Table 2.
Frequency of driving

Frequency	*Gr. 1*	*Gr. 2*
Once/month to Once/week	1	2
Everyday	6	5
Total	7	7

Table 3.
Kilometers covered during the last twelve months

Kilometers	*Gr. 1*	*Gr. 2*
< 10 000	2	7
10 000 – 50 000	5	
Total	7	7

Apparatus and materials

<u>Vehicle and warning display</u> – The vehicle participants were invited to drive was a Renault Magnum. The SafeMap warnings were presented on a display located on the dashboard as illustrated in Figure 1. The display was 9,2 cm high and 15,5 cm wide.

Figure 1. View of the Renault Magnum dashboard with the warning display.

SafeMap warnings – The warnings that were presented to the drivers consisted in speed, curve, accident spot and physical restriction warnings. Two warnings could be displayed at the same time but at different locations and size depending on priority rules. Figure 2 illustrates two warnings, one, in the central position, indicating that the driver is exceeding speed and another one on the upper left corner indicating an accident spot. In this example, the speed warning has priority over an accident spot warning.

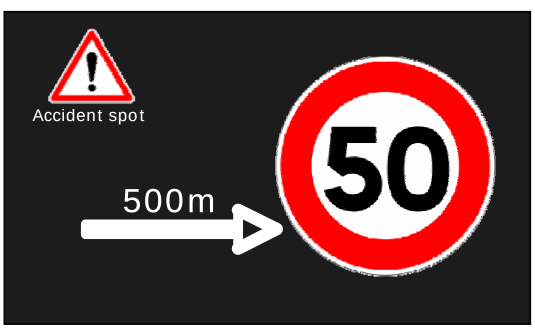


Figure 2. Example of a dynamic display of warnings.

The test track – The test track was located in the vicinity of the Lyon region. In consists of about 60 km and was chosen so as to ensure that a sufficient number of warnings would be triggered.

Data collection – Two small webcam were use: one to record the warnings displayed and another one to record the drivers' face so as to be able to see whether the drivers were looking or not at the warnings when they were displayed. The video images were recorded with the software CANape 6.0 which was installed on a portable PC. This PC was connected to the CAN bus of the truck. Thus, the position of the truck on the circuit in terms of distance traveled, speed, break pedal pressure, steering wheel angle, longitudinal acceleration as well as the code of the SafeMAP warnings displayed were recorded in real time simultaneously and unobtrusively.

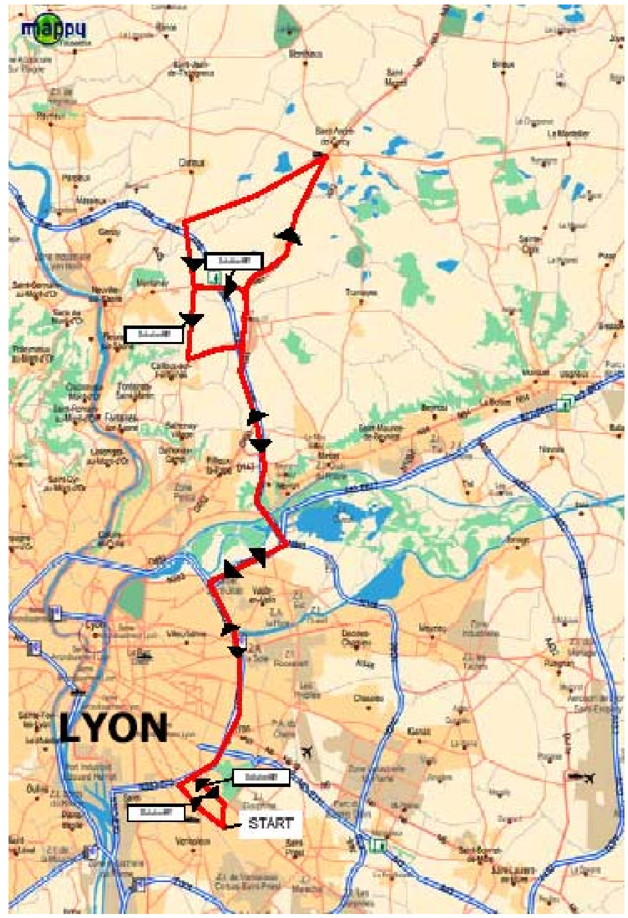


Figure 3. Route of the test track near Lyon, France.

Interview and questionnaires – To evaluate drivers' acceptance of the warning system as well as getting subjective information on its characteristics, a questionnaire and a survey were administered immediately after the driving session. To measure the subjective assessments of usability, we used a modified version of the "System Usability Scale (SUS)" [5] a simple ten-item Likert scale. Drivers were also asked to assess the system on several pairs of adjectives describing the characteristics of the system on a bipolar scale ranging from -2 to 2. As for the survey, we used another questionnaire on different characteristics of the warning systems (position of the display, size of the warnings, frequency, etc.), with questions on the understandability of the warnings as well as their dynamics.

Procedure

All the driving sessions occurred at daytime under good weather conditions (dry weather).
At the arrival at the start point of the circuit, the recording equipments were switched on and the instructions were given to the drivers. We used a mixed design with "Group" as a between factor and "Run" as a within factor (Table 4). All the drivers traveled the circuit two times. For the drivers in group 1, the first run was done with the warning system off. Thus no warnings were presented to the drivers during their first run. For the drivers in group 2, the first run was conducted with the warning system on. Thus, depending on the drivers' behaviors and the location of the vehicle on the circuit, drivers could be presented with warnings. Although only the drivers in group 2 had the opportunity to experience the warning system on the first run, the behaviors of all the drivers were recorded continuously. After the first run, participants were invited to travel the circuit a second time. This time, the warning system was turned on for the drivers of group 1 and turned off for the participants of group 2. After the drive session, the questionnaires were administered to the drivers and an interview followed.

Table 4.
Warning system state

	Warning system state	
Group	*1st run*	*2nd run*
1	Off	On
2	On	Off

RESULTS

The effects of speed warnings on drivers' behaviors

Speed warnings were dependent on the drivers' behaviors. As such, speed warnings were only displayed when drivers exceeded the legal speed limits (50 km/h and 70 km/h). Thus, for each driver, the warnings appeared at different points on the circuit and for different durations. To be able to compare and analyze statistically the data between and within groups, the data files were filtered so as to keep only the data that were recorded without any loss or interruptions for each driver on the two runs. Then, different measures were computed such as the number of speed excess per minute and mean duration of the speed excess. The multivariate analyses of variance for repeated measures (MANOVA) indicate that there were no statistical effects for the group (F (1, 27) = 0.79, p = .393) and run (F (1, 27) = 0.18, p = .683) factors and no interactions between them (F (1, 27) = 1.18, p = .298) on the number of speed excess per minute.

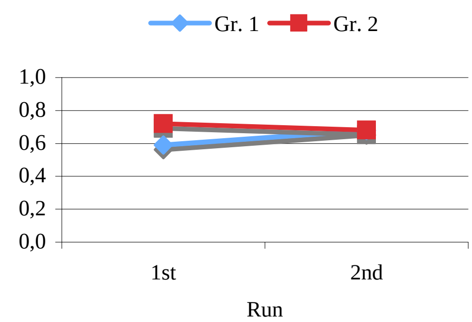


Figure 4. Number of warnings per minute for each group ruding the first and second run.

In other words, whether speed warnings were displayed or not had no effect on the number of speed excess. On the average, participants in group 1 exceeded legal speed limits 0.64 times per minute while participants in group 2 exceeded legal speed limits 0.7 times per minute. The data also indicate that drivers were quite coherent in the way they drove from the first to the second run. Globally, drivers exceeded speed limits 0.66 times per minute during the first run and 0.68 times per minute during the second run.
However, the display of the speed warnings had an effect on the duration of the speed excess. Although the MANOVA for repeated measures did not revealed a significant effect for group (F (1, 27) = 0.06, p = .807) and for run (F (1, 27) = 2.20, p = .164) factors, it revealed a significant effect of the interaction between the group and run factors (F (1, 27) = 9.91, p = .008) as illustrated in Figure 5. What the interaction shows is that drivers exceeded the legal speed limit for shorter period of time when they were warned about their speed limit excess as indicated by the post-hoc comparisons (F (1, 27) = 5.53, p = .027). Thus, duration of speed excess is shorter when drivers are warned, i.e. in the second run for drivers in group 1 (F (1, 27) = 5.99, p = .022) and shorter in the first run for drivers in group 2 runs although not statistically different (F (1, 27) = .77, p = .388).

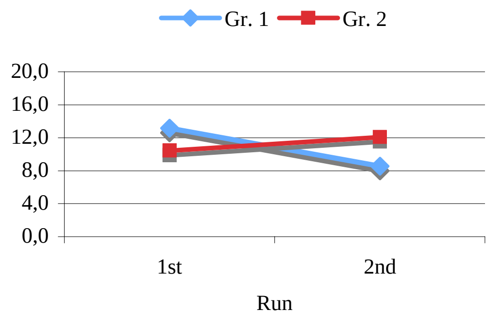


Figure 5. Mean duration of speed excess for each group during the first and second run.

The statistical differences found for the duration of speed excess is in fact due to the excess in speed for the legal limits of 70 km/h. Figure 6 illustrates the evolution of the duration of speed excess for each group during the first and second run for a 50 km/h legal limit. The MANOVA indicates no statistical effects for the two factors {group: (F (1, 27) = .97, p = .343); run: (F (1, 27) = .78, p = .394)} and their interaction (F (1, 27) = 1.64, p = .224). In other words, there is no statistical difference in terms of duration of speed excess whether the warnings are presented or not. The small decrease observes in group 1 is not statistically significant.

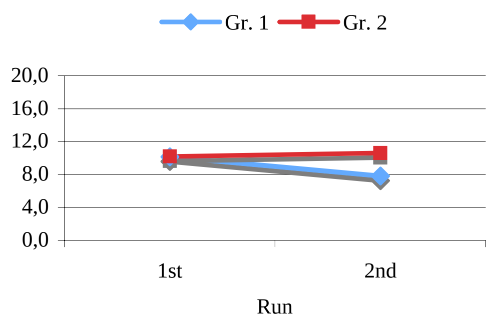


Figure 6. Mean duration of speed excess for each group during the first and second run for a 50 km/h legal limit.

However, the MANOVA for repeated measures computed on the duration of speed excess over 70 km/h showed a significant effect for the interaction of the group and run factors (F (1, 27) = 6.50, p = .026) (see Figure 7). On the average, the duration of speed excess is shorter (M = 10,85 s) when speed warnings are presented to the drivers (group 1, 2^{nd} run and group 2, 1^{st} run) in comparison to the runs were drivers are not warned (group 1, 1^{st} run and group 2, 2^{nd} run) for their speed excess (M = 17,80) (F (1, 27) = 4.52, p = .044).

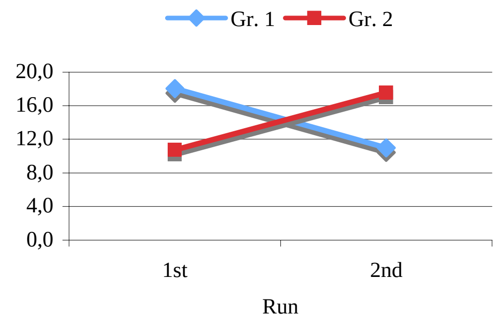


Figure 7. Mean duration of speed excess for each group during the first and second run for a 70 km/h legal limit.

The effects of curve warnings on speed

When the warning system was on, speed warnings were displayed when the actual speed exceeded the recommended speed calculated so as to ensure safety of the convoy given the curve geometry. For each driver, the speed was recorded continuously whether the warning system was on or not, thus allowing the assessment of the impact of the warning in comparison to the run during which the warning system was off.

Here again, the data files were filtered so as to keep data that could be compared for the 12 curves among all the drivers across the two runs. Two indexes were computed: (1) the percentage of the distance traveled in speed excess (with and without warnings) of the distance of the run, (2) and the percentage of distance traveled in speed excess (with and without warnings) of the cumulated distance of the 12 curves.

The MANOVA for repeated measures did not revealed any statistical effects. There was no effect of group (F (1, 27) = .28, p = .607), no effect of run (F (1, 27) = 1.98, p = .185) and no interaction (F (1, 27) = 2.26, p = .159) in terms of percentage of the distance traveled in speed excess of the distance of the run (Figure 8, Gr. 1 and Gr. 2). The same statistical conclusions are drawn for the percentage of distance traveled in speed excess of the cumulated distance of the 12 curves: there are no statistical differences between groups (F (1, 27) = .47, p = .505), between runs (F (1, 27) = 1.87, p = .197) and no statistical interaction (F (1, 27) = 2.03, p = .179). In other words, the curve warnings had no statistical effects on speed. Drivers' behaviors in curves did not differ from one run to the other with and without the curve warnings.

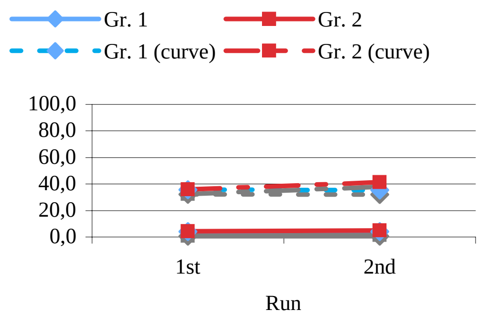
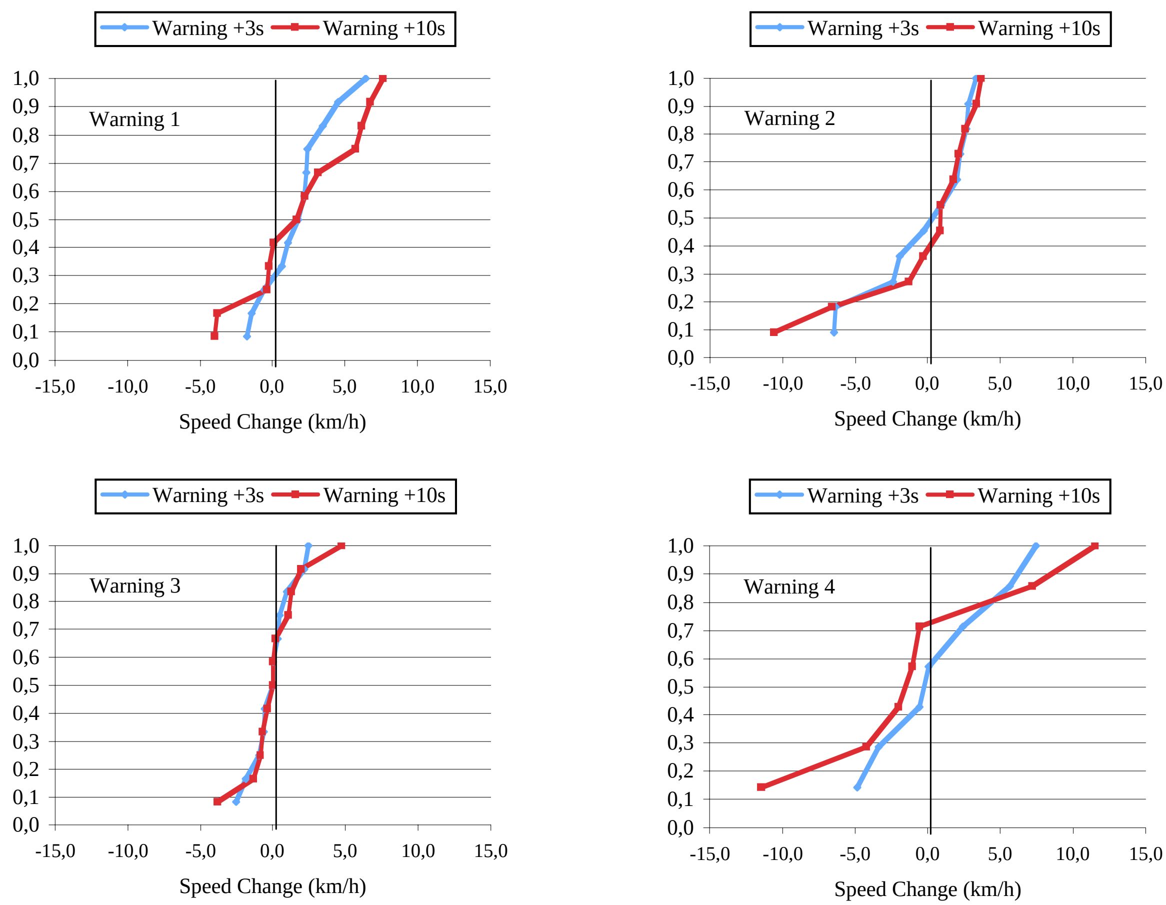


Figure 8. Percentage of distance traveled in speed excess.

The effects of accident spots warnings on speed

Six accident spots were analyzed. For the analysis, the speed of the truck was considered, from 10 s prior to the accident spot (whether the warning was displayed or not) to 10 s after it. To assess the impact of the warning we: (1) compared the time period before the warning to identify any general change in speed between the two runs for each driver, (2) compared the time period after the display of the warning to identify a change in speed after the warning was displayed, (3) subtracted the general speed change from the speed change after the warning was displayed to isolate the effect of the accident spot. Two time period were considered for the analyses after the warning points: 3 s and 10 s. The figures that are presented hereafter (**Figure 9**) concern only the drivers that were unaffected by cars ahead.



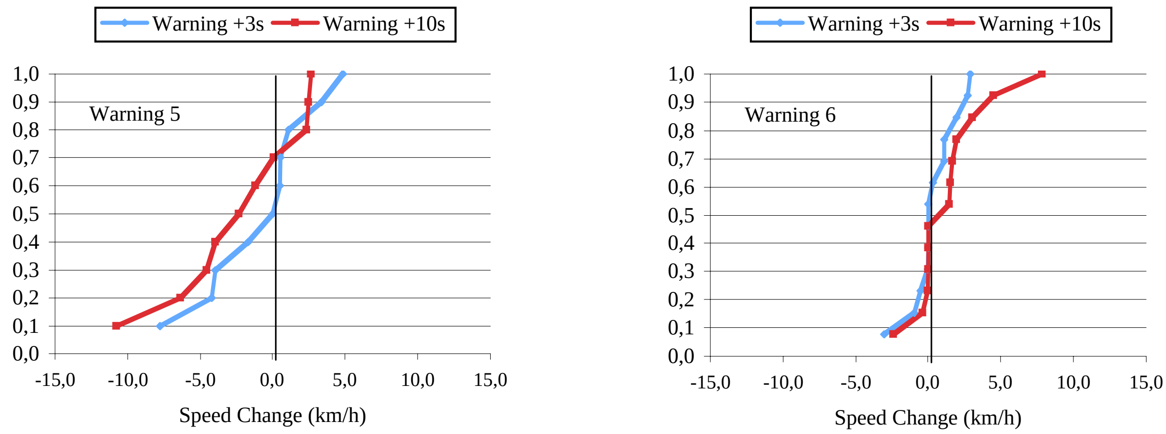


Figure 9. Cumulative percentage of absolute speed change 3 and 10 s after the accident spot warning onset.

These graphs show that the impact of the accident spots warnings on speed is variable from one accident spot to another and that the variations in speed, i.e. decelerations and accelerations vary among drivers. For example, the accident spot warning number 3 induced, 3 s after its onset, a decrease in speed ranging from 0.56 to 2.55 km/h in 42% of the drivers. On the other hand, 42% of the drivers increased their speed from 0.34 to 2.43 km/h. This tendency is almost the same 10 s after the onset of the warning. On other accident spots, the decrease in speed for some drivers and the increase in speed for others is greater as illustrated for warnings 2, 4 and 5. In other words, the characteristics of the road at these accident spots may have increased the effect of the warnings. When the tendency of drivers to decrease their speed continues after 3 s, the red lines on the figures are above the blue ones.

The effects of physical restrictions warnings on speed

Two physical restriction warnings were also analyzed in terms of the impact they had on speed. The approach taken to present the results is identical to the approach adopted for the accident spots warnings. As for the accident spots, the impact of the warnings on speed varies as a function of the driver. As shown in Figure 10, three seconds after the onset of the warnings a decrease in speed between 0.79 km/h to 4.57 km/h was observed in 44% of the drivers on the first physical restriction (PR 1). However, 56% of the drivers increased their speed from 0.57 km/h to 4.92 km/h. The decrease in speed continued after 3 second, and 10 seconds after the onset of the warnings, 67% of the drivers had decreased their speed between 0.86 to 6.92 km/h. The other 33% of the drivers, although they were above the speed they had before the onset of the warning were "slowly" decelerating, as indicated by the upper part of the red line in Figure 10, PR 1.

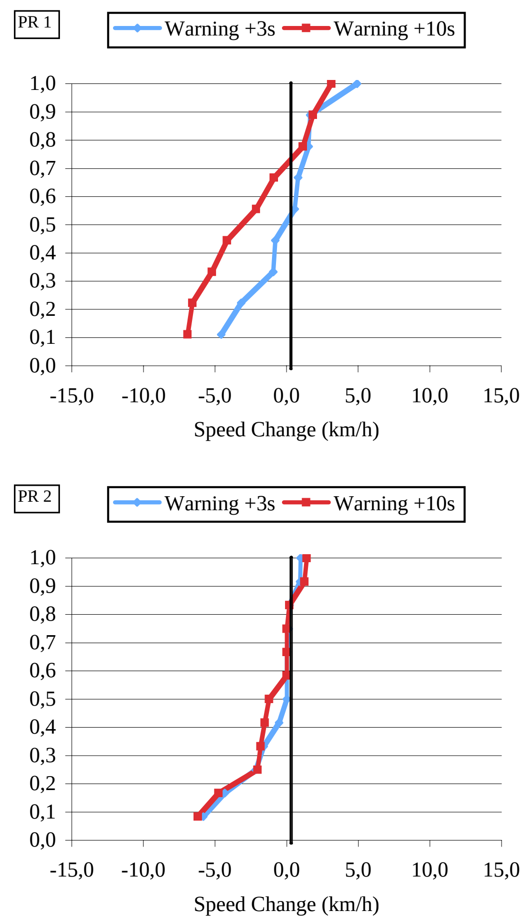


Figure 10. Cumulative percentage of absolute speed change 3 and 10 s after the physical restriction (PR) warning onset.

On the second physical restriction (PR 2), a decrease in speed ranging from 0.52 to 5.81 km/h was observed in 42% of the drivers 3 s after the onset of the warning. In this second physical restriction area, warnings had no effect in speed in about 30% of the drivers. The other drivers (28%) showed a very slight increase in speed ranging from 0.13 to 0.97 km/h. Ten seconds after the onset of the warning, 83% of the drivers kept their speed constant or continued to decrease it from 1.22 km/h to 6.2 km/h.

Drivers' assessments of the warning system

Results of the adjective pairs questionnaire - After the test runs, drivers were invited to complete two scales. The first was used to assess the system on 9 pairs of adjectives. To get the drivers' attention to the pairs of adjectives, the positive and negative items were randomly changed from right to left. Figure 11 presents the mean scores on each pair of adjectives. Here the positive items are presented on the right.

As is illustrated in this figure, the evaluation is rather positive although some pairs of items got only small positive judgment. Drivers judged the system useful, good and desirable. However, the system received a low score on its helpfulness and activating aspects. Nonetheless, no pairs of adjectives got negative scores.

The System Usability Scale results - To measure the usability of the system, drivers were invited to complete a modified version of the "System Usability Scale" (SUS). The SUS was modified because the system being evaluated was not an interactive system in the usual sense. Drivers could not interact with it. Thus some statements of the SUS were modified so as to be more adapted to the warning system. The results of this scale are illustrated in Figure 12. As with the previous results, all the drivers' positions with respect to the statements are positive. The scores that are lower than 0 concern negative statements. In other words, disagreeing with a negative statement means agreeing with its positive counterpart. For example, on the average, drivers said they rather disagreed with the statement saying "They found the warnings difficult to understand" (-1). This result is thus positive. All the scores except one, which is 0, are positive. Scores that are equal or higher than 1 concern 4 statements out of 10. These statements concern the understandability of the warnings, the context of use of the warning system, the non-nuisance character of the system, and the learnability of the system.

Figure 11. Results of drivers' survey of the system.

In other words drivers found the system rather easy to learn and understand. They said they would use the system even in vehicle they are familiar with and that the warnings constitute no nuisance. With scores that were lower, drivers said the system was not superfluous, the warnings adequately reflected the situations encountered and that they were well informed. However, the mean score to the statement "I drove more safely with the system" was 0.

CONCLUSION

The aim of this research was to assess the impact of speed limit, curve speed, frequent accident spots and physical restrictions warnings on driving and to evaluate the drivers' acceptability of these warnings. The results presented in this paper indicate that the speed limit warnings had no effects on the number of times drivers exceeded speed limits but decreased the duration of the speed excess and that this effect was essentially true for the 70 km/h speed limit. The effect of curve warnings had no specific effects on speed. The accident spot warnings showed variable effects. On some accident spots, the warnings induced a decrease in speed although a small one. As for the physical restrictions warnings the effects were different for the two warnings. The range of speed decreases for some drivers but increased for others.

The comments that were collected after the test runs towards the warning system were rather positive and drivers provided good ideas to improve the warning system.

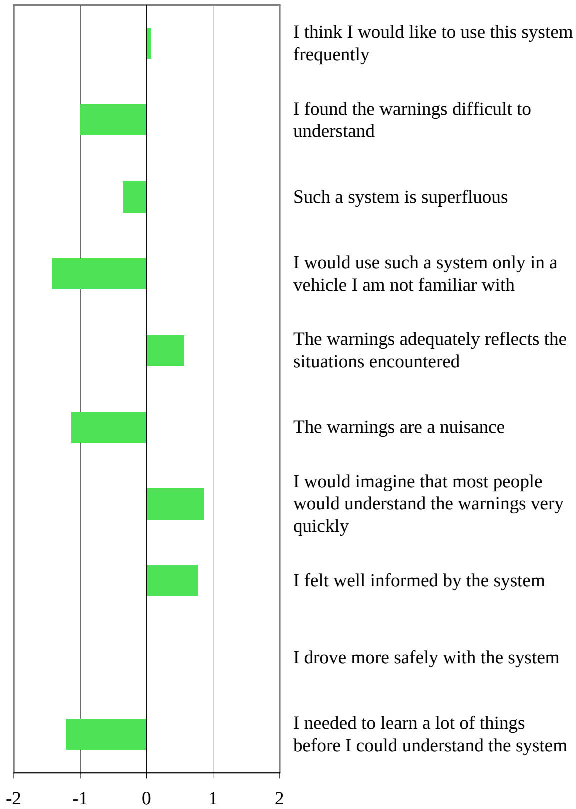


Figure 12. Drivers' mean scores to the modified version of the System Usability Scale. The original Likert scale was transformed so as to present the scores in comparison to the neutral position (0). The -2 score represent a "Strongly disagree" position while the 2 score represents a "Strongly agree" position with respect to the statement.

Although the impact of the warnings on speed may not be as high as one would have liked, caution should be taken before concluding. Speed may not be the best index of the warning impact: being warned of different situation may increase the attentional processes and situation awareness of the drivers without having any effect on speed. On the other hand, people react differently to warnings and if even a small portion of the drivers react with a decrease in speed, this could probably save lives. As such, the SafeMap system may be a promising tool to assist the diver in critical situations and thus avoid accidents. But such a tool would necessitates more research on the design of the warnings, its placement in the dashboard and its acceptability.

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FRENCH STUDY TO ENHANCE PASSIVE AND ACTIVE SAFETY ON MILITARY VEHICLES

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ABSTRACT

An ETAS study (ETAS is a French MoD RDT&E facility) was launched for reducing fatalities and damages due to traffic accidents involving military vehicles. Such vehicles were indeed identified as being subject to specific constraints bound to their particular operational use. Therefore, the French Defence Procurement Agency (*Délégation générale pour l'armement, DGA*) and Altran Technologies conducted for two years a joint study with the following goals:

1) identify the main drivers of traffic accidents involving military vehicles through a statistical survey over the past decade;
2) identify and assess active and passive safety systems able to mitigate traffic accidents without altering military vehicles' operational capabilities;
3) draw the specifications of safety demonstrators to be manufactured, implemented and tested later on.

Tasked by the DGA, Altran technologies conducted a statistical survey using the French Army data on traffic accidents in metropolitan France, overseas territory, and operational theatres. At the end of the survey, the results clearly showed that occupants in military vehicles run peculiar risks given specific uses and designs of such vehicles. In order to identify relevant technical as well as feasible solutions, the DGA and Altran technologies established new state-of-the-art of active and passive safety systems list of requirements/designs. The results show that the emphasis shall be put primarily on finding ways to improve:

- static and dynamic stability;
- traffic lights efficiency;
- inter vehicle compatibility;
- occupants restraint systems' efficiency.

For each of the themes, Altran Technologies defined a set of requirements that shall permit to improve the overall safety of the military vehicles during retrofit and design activities.

INTRODUCTION

The French MoD tasked Altran Technologies to conduct a study program aiming at reducing human and material losses due to traffic accidents involving military vehicles out of military operations activities. Accidents concerned included open road accidents appending on national territory or during transport activities in extra territorial operations.

Focusing on high traffic vehicles, this study distinguished different categories of vehicles such as light vehicles, heavy logistics trucks, heavy trucks with trail, armoured wheeled vehicles and armoured track vehicles.

This program was made up of different parts as detailed in this document which were meant to be exhaustive towards all potential active or passive security systems that shall improve the safety of the military vehicles. The main goal is to define technical requirements for future vehicles or necessary evolutions that will leverage the benefit of civilian safety systems developed by the automobile industry.

GENERAL SURVEY

In order to identify the main driver of traffic accidents involving military vehicles, the first step of the study program was to conduct a statistical survey involving military vehicle accidents over the past decade. Three sources of information were used in order to fill up this database (see figure 1):

- the technical service for road and highways of the French MoT (Service d'Etudes Techniques des Routes et Autoroutes, SETRA);

- the French land forces staff (Etats-Majors de l'Armée de Terre, EMAT);
- the regional land forces legal departments (Service contentieux des commissariats des régions terre).

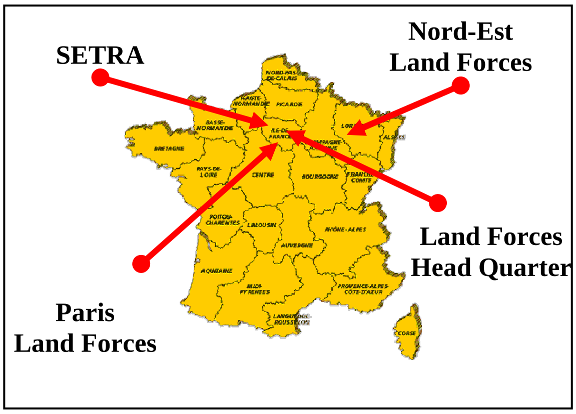

Figure 1. Data sources for home country and external operations accidents

A structured database was built up in order to identify the facts necessary for the identification of the most exposed vehicles and the main causes of accidents. In order to restrain the study to relevant cases, only the accidents that satisfied either one of the three following conditions were taken into account:

- severe injuries or fatalities of civilians or military personnel;
- material losses estimated at more than 10,000€;
- failure of the military mission due to the accident.

The information registered in this database was focused on the type of vehicle involved in the accident, the conditions of the accident, and the damage and fatalities resulting from it (see example in figure 2) .

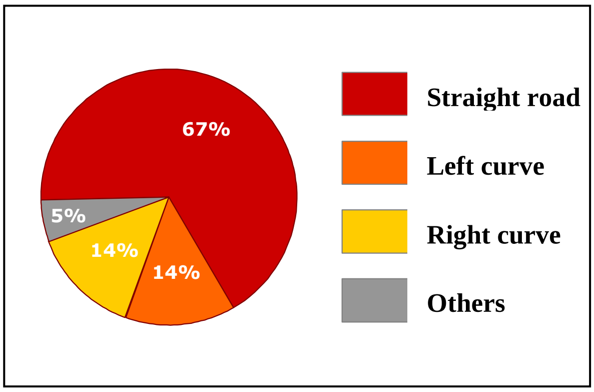

Figure 2. Accident data : road profiles

Over 900 accidents involving one or several military vehicles have been identified. For each kind of vehicle, it was estimated the ratio of the number of accidents vs the number of travelled km (see figure 3). The analysis of these data permit to identify the main causes of military vehicle accidents:

- due to design constraint the military vehicles are not appropriate to operate on roads and highways;
- the military personnel are not trained enough in order to safely operate the military vehicles.

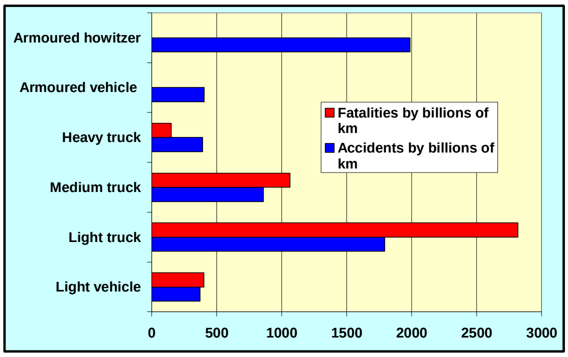

Figure 3. Number of road accidents by type of military vehicle

The military vehicle designs are subject to operational requirement including discretion. The colour and the signalisation lights are defined to ensure the maximum discretion and therefore safety during military activities. However, this discretion becomes a threat on the road: military vehicles are not as visible as civilian's and their signalisation lights do not permit other drivers to clearly understand the behaviour of the vehicle. Indeed, 80% of the accident between two vehicles in the same lane is back shocks for the military vehicle generally explained by a bad perception of the vehicle's behaviour or speed.

The second identified cause of accident through the statistical survey is training and insufficient experience of military personnel towards their capacity to drive and operate military vehicle. In 70% of the accident, drivers were under 25. By their design and specifically their off-road capacity and high charge capacity, military vehicles are not easy to operate on road or highways. The military vehicles off-road capacity and the armoured structure are the origin of instabilities and specific behaviour that can only be handled by a well trained and experienced driver. Despite the fact that the driver respected speed limits, in 25% of the accidents, the vehicle's speed was considered inappropriate.

These two causes are significant in accident risk for military vehicles. In addition, the statistical survey identified two other causes that lead to an increase of the accident consequences:

- military vehicles' designs are not optimized for accident damage mitigation;
- military vehicles' seats and restrain systems are not optimized for injury mitigation.

The off-road military vehicles' design is not appropriate for damage mitigation especially with civilian vehicle. On one hand, this configuration exposes vehicle vital organs to shocks like the drive axle. The study underlined that 40% of the damaged vehicles are not economically repairable. On the other hand, the relative height of the military vehicles is a real threat for the civilian vehicles' occupants.

30 years old design vehicles are still in operation among the French forces. Those vehicles do not satisfy today's seats and restrain systems. The automobile sector has shown a significant amelioration of vehicle occupants' safety by an improvement of the seats and restrains systems design. A proper use of a restrain system can reduce by two the risk of severe injuries.

The statistical survey showed that in order to reduce the material damage and fatalities due to military vehicles' accidents, the French MoD will have to investigate active systems in order to reduce the number of accidents and passive systems in order to reduce the severity of these accidents.

STATE-OF-THE-ART SAFETY SYSTEMS

In order to provide valuable technical basis for recommendations, Altran Technologies has conducted a state–of-the-art analysis of the actual and future active and passive safety systems that are in operation in the automobile sector (see figure 4).

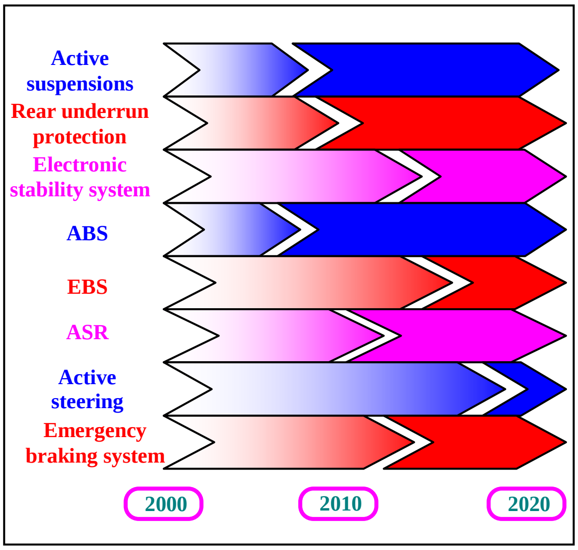

Figure 4. State-of-the-art and future developments of the active stability system concerning military vehicles

The active safety systems have been distributed among three categories:
- stability improvement and control systems;
- driver assistance systems;
- collision avoidance systems.

The evolution of the active safety systems is characterized by the integration of automated control loop systems over the various components of the vehicle. Generation after generation, this systems increased their time integration capacity as well as the number of parameters that they are able to integrate e.g. from Anti-lock Braking System (ABS) to Emergency Brake Assist (EBA) to Anti-Skid Resolution (ASR) and Electronic Brake-force Distribution (EBD).
The passive safety systems have been distributed among three categories:
- occupants' protection;
- vehicle protection;
- close environment protection.

The evolution of the passive safety systems is characterized by a progressive protection of the outside of the vehicle. A few decades ago, the engineers started improving the occupants' protections through the optimization of restrain systems and the development of airbags. Later on, the technical efforts were oriented towards reinforcing the passengers' compartment in order to avoid any deformation of this safety space. Today, research programs aim at reducing the risk the vehicle may represent toward its close environment like the others vehicles or the pedestrians.

The sate-of-the-art safety system identification provided several axis of improvement through the integration of actual or near future technology from the civilian automobile sector.

AXIS OF SAFETY IMPROVEMENT

In order to mitigate the risk of military vehicles' accidents, Altran Technologies identified four axis of improvement that shall be primarily addressed in order to scientifically reduce the number of accidents and the severity of the damages and fatalities:
- improvement of the vehicle's static and dynamic stability in order to ease the driving;
- improvement of the signalisation lights' effectiveness in order to better inform the other drivers;
- improvement of the inter vehicle compatibility in order to reduce material damages and fatalities;
- improvement of the seats and restrain systems in order to reduce the injuries due to the accident.

To ease the driving of the vehicle and therefore compensate the drivers' lack of experience, the vehicle shall integrate an active safety system that shall improve its stability. The first step was to improve the static stability of the vehicle through an optimization of the brakes, suspensions and the tires. Then, a research program was undertaken in order to evaluate the benefits of dynamic systems such as the ABS or ESP. The preliminary studies show that the static stability speed limit is close to the speed limit of the vehicle in normal operational conditions with no security margin: through the integration of active systems or by limiting the vehicle's speed of operation this speed limit shall be raised at least 20% above the maximum operation limit speed in order to avoid any specific unexpected behaviour of the vehicle.

Over the past 5 years, lots of breakthroughs have been accomplished by the automobile and electronic sectors in the field of signalisation. The actual military vehicles' signalisation lights are designed under discretion requirements and classical light bulb systems. The LED technologies are presently replacing the old signalisation system with a better efficiency and management of the light intensity. A research program has been proposed in order to develop an adaptive signalisation light system that shall be able to meet the discretion requirements during military operations but still warn other drivers of the vehicle's manoeuvres with no ambiguity.

The actual military vehicles' designs do not allow a mitigation of damage and fatalities in case of an accident generally resulting from the all-road conception. During the past decade, several study programs were undertaken and regulations were implemented in order to prevent the threat that represents a heavy truck to light cars or motorbikes. Altran Technologies recommends implementing these systems as soon as possible on the current land forces vehicles in order to meet the civilian regulations and to prevent any fatalities that will legally consider as "fragile skeleton" issue.

Through the past decades, the occupants' safety systems have evolved and the safety regulations have progressively integrated this evolution by taking into account the technical progresses achieved by the automobile sector. At present, some old vehicles have no restraint systems (see picture 1). Three points restraint system for all occupants, airbag system for front occupants and reactive seats are today standard in the automobile sector. Altran Technologies recommends undertaking retrofit programs in order to upgrade the actual military vehicles to civilian standard and ensure the safety of the military personnel.

Picture 1 : example of an old military vehicle without restraint systems

The detailed analysis of the opportunity for safety improvement shows that a significant safety improvement can be achieved by implementing the actual automobile sector safety standard to military vehicles.

CONCLUSION

Designed for most of them during the 60's and the 70's, military vehicles were at the edge of the technology at that time. However the acceleration of new research and developments in the automobile sector during the past decade as well as advances in the transportation infrastructures and the social perception of driving risks made this systems nearly obsolete and bring the urgency of actions to be undertaken in order to improve the safety of the military vehicles.

The study program shows that several available civilian safety standards could scientifically reduce the number of military vehicles' accidents as well as the damage and the fatalities due to these accidents.

In the near future, the integration of the civilian safety standards to the military vehicles shall make it possible to divide by two the number of accidents and save lives and money to the French Army.

LABORATORY TESTING PROGRAM FOR F.E. CRASH ANALYSES OF PARATRANSIT BUSES

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ABSTRACT

An extensive validation program was developed and implemented in support of computational mechanics of paratransit buses. The program is based on laboratory testing of coupons for material characterization (test level 1, TL 1) and connection tests (TL 2). Experimental data obtained from TL 1 tests were used for development of the finite element (F.E.) models of several structural components and connections of a paratransit bus selected for this study. The segments, critical for crashworthiness performance of the entire bus, included: a wall-to-floor, a wall-to-roof, and a side-wall panel of the bus. Resistance functions, relating a force applied vs. resulting displacement, were developed for each component. They were obtained from experimental tests (at TL 2) and from computational mechanics F.E. analyses. Comparison of the resistance functions and the failure mechanisms provided a good validation of the F.E. models of the major structural components which, in turn, were included in F.E. models of the entire paratransit bus.

A model of the paratransit bus, with 600,000 finite elements, was developed for crashworthiness and safety assessment of the bus. AutoCAD files, material samples and components for testing were provided by the bus manufacturer to aid in the model development and validation processes. The Ls-Dyna nonlinear commercial code was used as major tools for numerical analyses. Two impact scenarios were considered: a rollover of a bus from 800 mm, and a 90^{o} side impact of the bus by a pickup truck at 48 km/h.

1 INTRODUCTION

Paratransit buses are defined as smaller buses usually carrying from 9 to 24 passengers. They are also known as public service vehicles (PSV) in England, minibuses in Europe, and omnibuses in Australia. Paratransit services are offered by public transit agencies, community groups, schools and churches, and they are often used to transport students and passengers with disabilities [1]. Even though the significant mass of these buses makes them invulnerable in front- and rear-end collisions, roof crash and side impact collisions remain two major concerns for crashworthiness and safety assessment.

Paratransit buses are usually built in two stages. The chassis and the cab are first assembled by one manufacturer, and then the body and relevant equipment are installed by another manufacturer. Since there are no well-defined industry standards for paratransit buses in the US, especially for the bodies built at the second stage, each body manufacturer has its own body design and connection details. Therefore, there is a need for conducting crash and safety assessment of this kind of bus. It is recognized that finite element simulation provides viable information of the bus structural performance in crash scenarios if the FE models are validated.

This paper concentrates on laboratory testing of coupons for material characterization and component testing for connection strength implemented in support of the development of the FE models of a selected bus (Figure 1).

Figure 1. A picture of a paratransit bus.

2 MATERIAL COUPON TESTING

LS-DYNA, a nonlinear, dynamic finite element code, is used for the crash simulation. In order to realistically represent the vehicle dynamic behavior, reliable material parameters should be first determined from laboratory tests. Four material types were selected for laboratory structure-property quantification, including:

1. A metal sheeting 0.58 mm thick used as the outermost layer of the passenger compartment.
2. The metal sheeting is glued with a thin layer of plywood to form a sandwich-like cover. This composite is further covered with foam for improved insulation and vibration damping.
3. Structural material used for the passenger compartment includes box tubing sections (HSS) and C channels that are welded together to form a distinct cage.
4. A ¾ inch plywood sheeting is typically used as a floor structure.

The steel coupons from the outer skin were prepared after removing the plywood part. For the structural steel, the test specimens were cut from the hollow section HSS 38.1x38.1x1.6mm which represents most of the bus body. A Computer Numeric Controlled (CNC) milling machine with a jig and a high tolerance cut (of 0.05 mm) was used to reduce the residual stresses in the test specimens. For steel coupons, spark spectrometry tests were first performed to determine their types. The spectro-max machine indicated that the materials were SAE 10xx series steel. Tensile tests were next conducted using an Instron 5865 machine, which is an electro-mechanical material testing machine using a PID feedback loop to monitor the extension of the specimen for a constant strain rate on the specimen. Figure 2 shows the setup of the steel coupon testing.

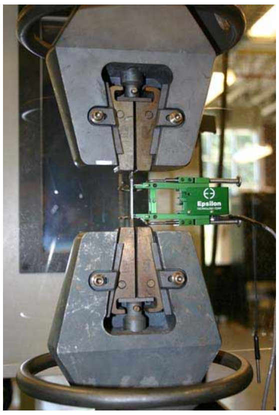

Figure 2. A coupon test of an outer layer of the bus wall.

The stress strain relationship is presented in Figure 3, and the material parameters, along with the MatWeb data [2], are listed in Table 1.

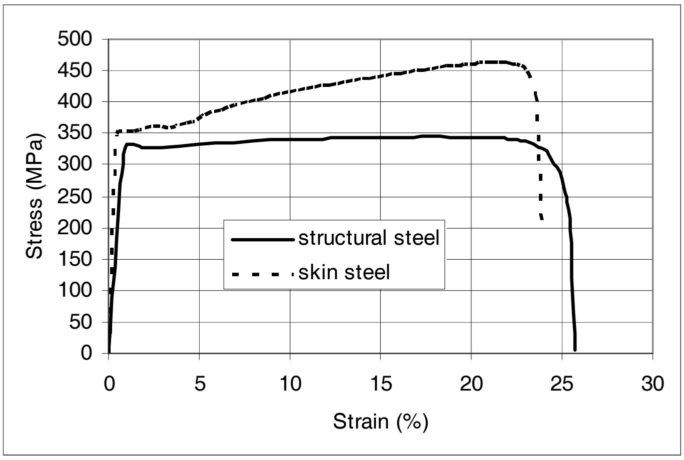

Figure 3. Stress vs. strain diagram from tensile tests of the outer skin steel and structural steel.

Table 1.
Material characteristics for skin steel and structural steel

	Ultimate strength (MPa)	Yield strength (MPa)	Elongation at break (%)	Reduction of area (%)	Modulus of elasticity (GPa)
MatWeb data for AISI 1010	365	305	20	40	205
Outer skin steel	463.2	346.38	23.9	37.95	186.66
Structural steel	345.54	315.49	25.8	43.9	165.17

For structural steel, the ultimate strength and yield strength are close to those of AISI 1010 steel, while the Young's modulus is significantly lower.

However, both the ultimate strength and yield strength of the skin steel are higher than the AISI 1010 values. This is due to the work hardening of steel during successive rolling processes required to obtain a very thin sheet.

The external wall of the bus is made of a thin steel sheet (0.58 mm thickness) glued with a thin layer of plywood (3.45 mm thickness). The properties of the metal part were determined by the tensile test as described above. Further testing was needed to find the properties of the thin layer of plywood. Due to the significant difference of compression and tension resistance of both materials, a tension test was judged as inappropriate since the plywood would crush in tensile testing machine grips. A sample of the bus skin with 100 mm long and 13 mm wide was cut for three-point bending test. This test was performed per ASTM C-393 standards in a test fixture and loaded using the Instron 5869. The support span was set as L = 80 mm, and a mid-span deflection was recorded as a function of the load applied at the midpoint of the beam. The force vs. deflection relationship is shown in Figure 4.

Figure 4. Force vs. deflection diagram from the three-point bending test of the outer skin consisting of steel and plywood.

From the force-deflection relationship, along with the known material properties of the steel layer, the properties of the plywood are determined with the assumption of elastic-plastic material. The parameters are listed in Table 2.

Table 2.
Material properties of the plywood in outer skin

Initial modulus (MPa)	Tangent modulus (MPa)	Yield strength (MPa)	Failure strength (MPa)
1500	300	14.81	20.0

A simple finite element model of the composite skin was developed with LS-DYNA to verify the obtained properties. With the steel properties and plywood properties assigned to corresponding layers, finite element analysis generated the force deflection curve which matches well with the tested curve shown in Figure 4.

Inexpensive 7-ply plywood is a common material for the bus floors. Due to the construction of the wall-to-floor connection, it was found that the floor (plywood with unknown grade) contributed to the load transfer from the sides of the bus to the frame during side impact and rollover accidents.

A segment of plywood was cut into 50.8 mm wide and 610 mm long for four- point bending beam test. The test setup is depicted in Figure 5.

Figure 5. A four point bending test of a plywood sample from the bus floor.

MTS LX 500 laser extensometer was used to measure the displacement at the mid span of the plywood sample (Figure 5). The measurement error was limited to +/- 0.001 mm. The flexure modulus of elasticity is 7.42 GPa and the maximum stress at break is 22.58 MPa.

3 COMPONENT TESTING

Simple pendulum testing can provide valuable information about actual dynamic properties of segments cut off from the bus body structure. Not only it will indicate how stiff the panel is under impact loading, but also it provides data for finite element model validation. A representative body panel was cut off and supported by two steel I shape beams (Figure 6). The impacting energy should be carefully selected. For example, an underestimated impacting mass leads to small deflections and poor validation of the assumed nonlinear material models. Excessive deflections due to overestimated impacting mass are useless for numerical simulation – the tested element is damaged, and no sufficient information about its behavior can be obtained. The best approach is to create FE models of the tested panels and run computer simulations first before the experiment. In this way some of the experiment parameters such as an impacting mass and its initial position can be estimated. The experimental setup for the bus wall panel, as well as the FE model is shown in Figure 6.

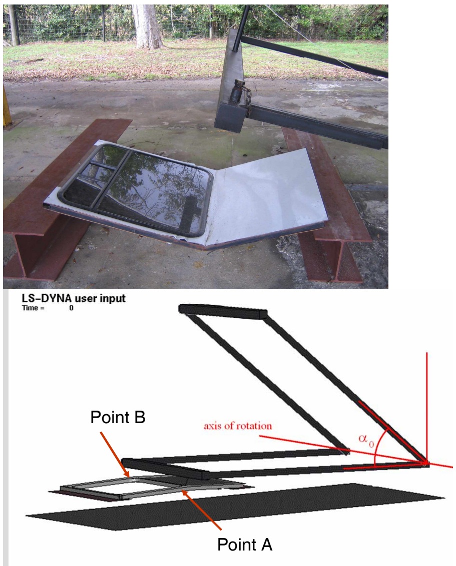

Figure 6. An impact hammer test of a bus wall panel and the FE simulation.

The impacting beam was 2.45 m long. The length of the arms was 3.02 m. The total mass of the hammer was 70.8 kg. In the testing, the hammer was raised to a height of 3.0 m and released. Before the hammer touched the panel, the impact velocity was about 7.67 m/s. The measured permanent deflections are 46 mm at point A and 48 mm at point B. Figure 7 shows the results of FE simulation.

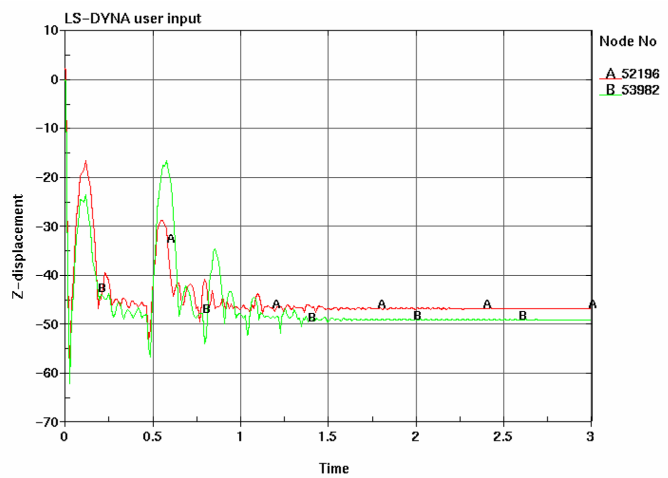

Figure 7. Displacement response of point A and point B on the panel under hammer impact from FE simulation.

It is found that the dynamic response of the panel is not symmetric because a non-symmetric internal square tubing is located across the lower part between the window and the bottom of the panel. After 1.5 seconds, the displacements approach constant values which indicate the permanent deflections. The calculated deflections at point A and point B are 47 mm and 49 mm, respectively.

The strengths of wall-to-floor and wall-to-roof connections play an important role for the crashworthiness of the entire bus. Each manufacturer has its own method of building the connections. Figure 8 shows the details of the wall-to-floor connection and Figure 9 presents the setup of the wall-to-floor testing.

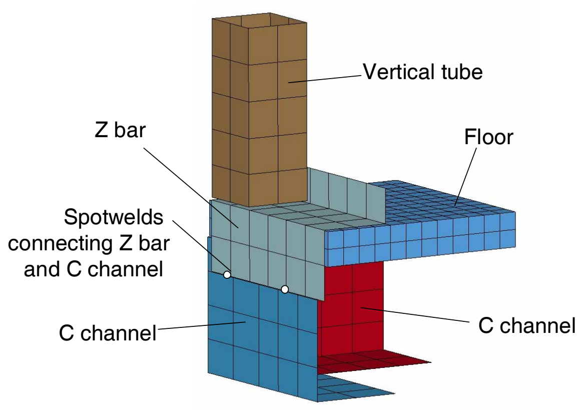

Figure 8. Details of the wall-to-floor connection in FE analysis.

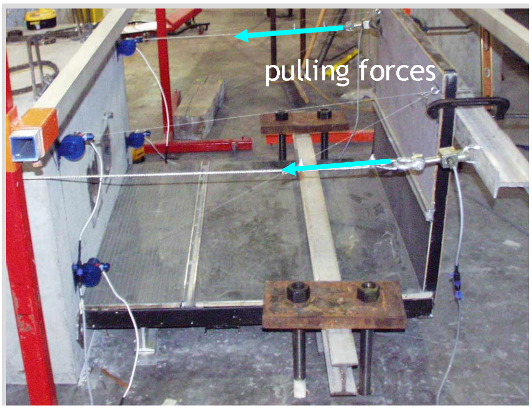

Figure 9. Setup of the wall-to-floor test.

Finite element models of the components were developed to simulate the testing process. The plywood floor was built from fully integrated solid elements with 8 nodes. The steel C channels, Z bars and vertical tubes were modeled with the 4-node fully integrated shell elements which are considered computationally efficient and stable. The average element size is chosen as 20mm after trading off between the accuracy and time step. PIECEWISE_LINEAR_PLASTICITY material model was used for the steel with the material parameters obtained from the tests as shown in Table 1. The model of the component consists of 34,000 finite elements (Figure 10).

Figure 10. FE model of the wall-to-floor connection.

The calculated moment vs. rotation curve is compared with that from the test as shown in the Figure 11.

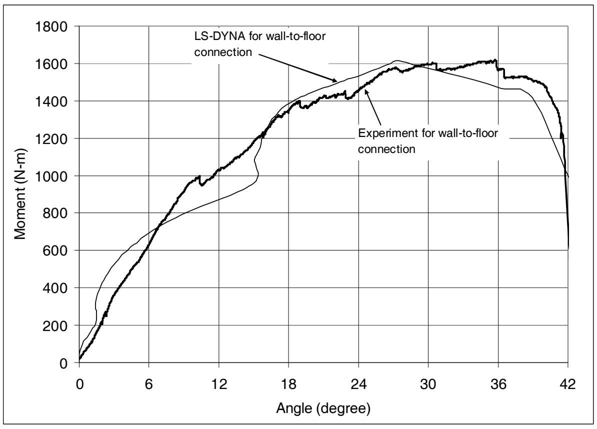

Figure 11. Resistance function for the wall-to-floor connection. Experimental data vs. finite element simulation.

The wall-to-roof connection was also tested using the same setup, and analyzed by FE models.

4 ROLLOVER AND SIDE IMPACT TESTING AND SIMULATION

Most developed bus testing standards can be found in the European Union (EU directives [3-4]) and the United Nations' Economic Commission for Europe (UN ECE Regulations [5]). Two UN ECE Regulations apply to the passive safety of coaches: Regulation 66 (Strength of Superstructure) and Regulation 80 (Strength of Seats and their Anchorages). Although these regulations are not yet mandatory in all of Europe, they are seriously considered by bus manufacturers during development and approval testing of new buses. UN ECE Regulation 66 describes rollover testing [6-7]. After the bus has been overturned onto the edge of its roof, a defined survival space (Residual space) must be intact. The vehicle is placed on a horizontal platform and then tilted (without rocking and without dynamic effects, angular velocity shall not exceed 5 degrees per second) until it rolls over. The tilt table is elevated by 800 mm above the concrete floor (Figure 12).

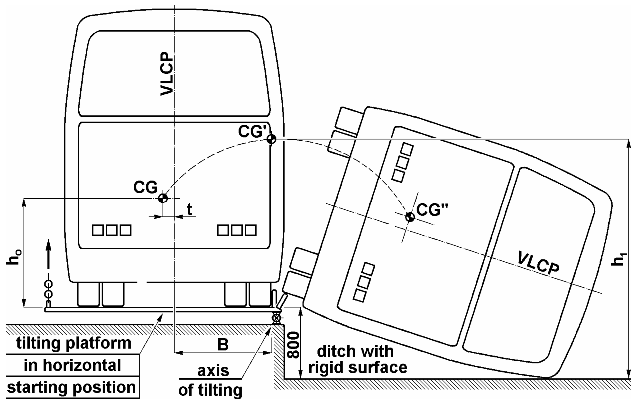

Figure 12. Rollover testing defined by UN ECE Regulation 66.

UN ECE Regulation 66 requires that the superstructure of the vehicle shall have sufficient strength to ensure that the residual space during and after the rollover test on the complete vehicle is uncompromised. This space is defined in [5]. This requirement constitutes a major pass/fail criterion established to provide a minimum survivable volume within the bus that is judged as necessary for mitigation of passengers' injuries. UN ECE Regulation 66 recognizes the need for finite element simulations as a viable source of information regarding crash and safety assessment of buses.

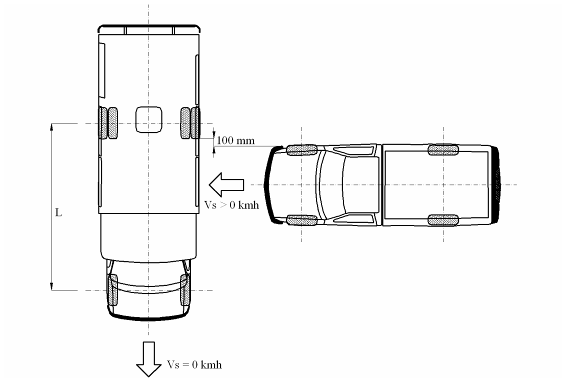

Figure 13. Setup for side impact by a pickup truck.

Another major concern about paratransit bus safety is side impact by a midsize pickup truck or an SUV. Due to the design tendency of lowering the bus floors coupled with the high location of bumpers in modern SUVs and pickup trucks, this impact scenario should not be ignored from the comprehensive bus crash and safety assessment program (Figure 13).

The tested material properties and validated component models were implemented in the whole bus model. A Ford Econoline chassis model, developed by the National Crashworthiness Analysis Laboratory (NCAC), was adopted to reflect that of the cutaway vehicle used for building the Champion buses. Modifications included extension of the wheelbase, adding wheels, new spring leaves and several others. The model of the bus body was separately developed based on the CAD drawings and was assembled with the chassis model. In the model development process, many questions arose considering mostly connections between the structural elements and their computational representation in the FE model. The model consisted of over 600,000 finite elements, and is described in detail in [8]. It was used to analyze two accident scenarios, 48 km/h, 90^{o} side impact by a pickup truck (Figure 14), and rollover test per Regulation 66 (Figure 15). The results will be presented in future publications.

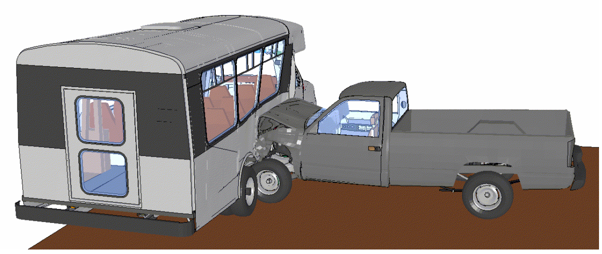

Figure 14. 48 km/h, 90^{o} side impact of the bus by a pickup truck.

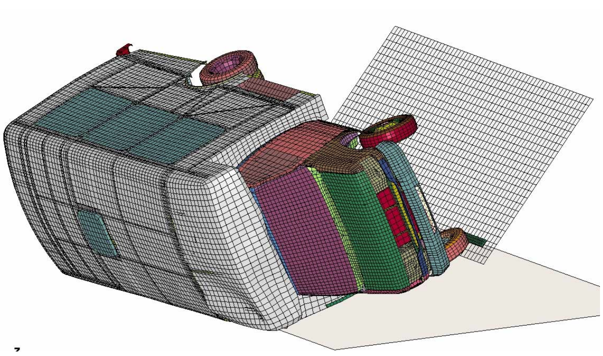

Figure 15. Rollover simulation of the bus from a tilt table, per Regulation 66.

5 CONCLUSION

Material characterization and component testing were conducted for a selected paratransit bus. The testing process, setup and results were presented in this paper. Material characterization from laboratory coupon tests was applied for the FE analysis which required reliable material parameters. Connection tests were used in turn for validation of the assumed material models, material properties and contact description at the component level. The validated connection models were implemented in the entire bus model dedicated for comprehensive analysis of the dynamic response of the bus during rollover and side impact accidents.

The testing process also allows for close investigation of the major connections which are responsible for keeping the residual space uncompromised per Regulation 66. It is highly possible that a bus with a strong passenger compartment but weak connections will fail the R 66 test. Good balance between the strength of structural members and the strength of connections is recommended for increased crashworthiness and energy absorbing.

Comprehensive crashworthiness and safety assessment of the bus in rollover and side impact accidents using the developed FE model is ongoing. The results will be discussed in our next papers.

6 ACKNOWLEDGEMENT

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