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CASUALTY PREVENTION BY SAFER FRONT END DESIGNS FOR HEAVY GOODS VEHICLES

ABSTRACT

Accidents involving heavy goods vehicles (HGVs) on European roads account for approximately 4,000 fatalities and over 15,000 seriously injured casualties per annum. Current HGV designs typically feature a flat front end, which does not afford optimal protection in accidents, and glazed areas of very limited size, which creates considerable blind spot areas in the vicinity of the vehicle.

An amendment to the weights and dimensions legislation, Directive 96/53/EC, will remove the current effective limitation of the HGV cab length. This offers an opportunity for legislators to mandate safer vehicle front end designs making use of the extended dimensions. This paper analyses the casualty reductions that could be expected from such requirements.

Design changes considered for this research were:

- Larger glazed areas to reduce blind spot areas in direct vision
- Tapered front end shape to prevent run-overs of vulnerable road users (VRUs) by deflecting them to the side
- Energy-absorbing frontal underrun protection systems to protect occupants of passenger cars in impacts more effectively
- Frontal crumple zones to improve the self-protection of HGV occupants in impacts with other heavy vehicles

Casualty numbers from the European CARE database were used to determine the current EU-28 target population size. A synthesis of published research on the effectiveness of individual design changes with an analysis of CARE data and STATS19 data (British police-reported accidents) was performed to determine the overall casualty prevention potential of the discussed measures on a predictive basis.

This update and synthesis of fatality prevention figures and the considerations regarding lower injury severity levels yielded a predictive estimate of potential reductions in road user casualties: The considered design changes might prevent 427–711 fatalities and 2,328–3,522 seriously injured casualties per annum across EU-28, which equates to monetary societal benefits of approximately 1.2 to 1.9 billion Euros.

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1 BACKGROUND

Heavy goods vehicles (HGVs) are involved in a disproportionally high number of fatal collisions; more precisely in about twice as many per distance travelled as the average vehicle (ETSC, 2013a). The casualties in these collisions are in most cases occupants of passenger cars (52% of fatalities) and vulnerable road users (VRUs) (33% of fatalities). HGV occupants are also fatally injured in collisions, but much less frequently (15% of fatalities).

An amendment to Directive 96/53/EC, the weights and dimensions legislation for HGVs, has been proposed by the European Commission (EC) to increase the design freedom for changes to the vehicle front ends that would improve aerodynamics (and therefore fuel economy) and road safety. Today, all HGV cabs have a similar design featuring a flat front end in order to maximise the interior space in the cab at a given cab length. The current legislation effectively limits the length of HGV cabs[1] which somewhat restricts the design of safe front ends.

It was proposed to grant derogation from this length limit on the condition that the changes in cab design lead to enhanced road safety (European Commission, 2013c). The Position of the European Parliament published in April 2014 suggested making safer cab designs mandatory after a certain lead time (European Parliament, 2014). The most recent political decisions might effectively delay the optional changes until the year 2022.

This change in legislation offers an opportunity to define mandatory technical requirements improving the design of HGV front ends, which might have the potential to improve the protection of VRUs, occupants of light vehicles as well as the occupants of HGVs themselves.

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[1] The length of the cab is not specifically limited; however, the limited maximum overall vehicle length and the commercial need to maximise the load space behind the cab in a competitive market effectively limits the cab length.

2 OBJECTIVES

The objective of this paper is to provide a predictive estimate of the number of casualties that could be avoided per year on the roads of the 28 member states of the European Union (EU-28) by design changes to HGV front ends. These numbers can inform the political decision process about the amendment of the weights and dimensions legislation for HGVs, which could enable and enforce these design changes.

More specifically, the annual casualty reduction potential in fatally and seriously injured casualties among the following road user groups shall be estimated on a predictive basis:

- VRUs: Protection by an improved field of view for the HGV driver and by vehicle front end shapes that deflect VRUs to the side in impacts to prevent run-over injuries.
- Light vehicle occupants (e.g. passenger cars): Protection by an improved, energy-absorbing front under-run protection.
- HGV occupants: Protection by crumple zones at the HGV front end.

3 METHODOLOGY

The following design changes to HGV front ends could be enabled by the change in legislation and were therefore examined for the magnitude of their casualty reduction potential. Note that all of the design changes are not yet used on the road and are also not specified in great technical detail, all effectiveness estimates are based on predictive studies which involve by their nature a high level of uncertainty.

- Improvements to direct vision. This applies mainly to the protection of VRUs from accidents where they were not visible to the driver. A typical case would be a run-over accident while pulling away from traffic lights.
- Improvements to VRU impact performance by vehicle front end shapes that deflect VRUs to the side in impacts to prevent run-over injuries. This applies mainly to low- and moderate speed run-overs. A typical case would be a pedestrian on the road in a built-up area being impacted by an HGV.
- Improvements to vehicle occupant protection by energy-absorbing front under-run protection and by crumple zones at the HGV front end. For light vehicles, this is most relevant in cases where high deceleration of the lighter vehicle or catastrophic deformation due to under-run occurs. A typical case would be a front-to-front impact between car and HGV. For HGVs, this is most relevant in cases where another heavy object or heavy vehicle is impacted. A typical case would be a frontal impact into the rear of another HGV.

The potential future casualty reductions by each of these design changes were derived by determining the size of the casualty target population and combining it with available information on their effectiveness: The target population size is the number of casualties of each severity level (fatally or seriously injured) that could potentially be influenced by the design change; the effectiveness is the proportion of the target population that would be prevented under the assumption of full fleet fitment. Multiplication of these figures results in the casualty reduction numbers.

The target population sizes were estimated by assigning to each design change a list of accident scenarios in which the outcome might be influenced by this particular change. For example, energy-absorbing structures mounted at the HGV front can be assumed to influence the outcome of HGV-front vs. car-front collisions, but not HGV-side vs. car-front collisions because the structures will not be engaged in this scenario. Published information from Volvo Trucks (2013) on the frequency of certain accident scenarios among fatally and seriously injured casualties in Western Europe (see Table 1) were applied to the overall EU-28 casualty numbers to estimate the target population size for each design change.

The effectiveness of each design change was estimated based on a review of published research and was defined as a range where more than one research project covered this specific design change. Key effectiveness estimates were used from the research by Welfers *et al.* (2011); Robinson *et al.* (2010) and Gwehenberger *et al.* (2004). No studies into the effects on slightly injured casualties could be identified, which is why this injury severity level was excluded from the further analysis.

Table 1: Accident scenario classification and estimated frequency among accidents causing fatal or serious injuries across Western Europe, reproduced from (Volvo Trucks, 2013)

Transport mode	Accident scenario	Description	Frequency
HGV occupants	A1	Truck single: Driving off road (with or without rollover)	35%
	A2	Truck single: Roll or yaw instability on road	15%
	A3	Truck- truck collision, oncoming traffic: Front vs. front	10%
	A4	Truck- truck collision, traffic ahead in same direction: Front vs. rear	20%
	A5	Truck-car collision, all collision types (if they cause injuries also to the truck occupants)	5%
Car occupants	B1	Truck- car collision, oncoming traffic: Truck front vs. car front,	35%
	B2	Truck- car collision, oncoming traffic: Truck side vs. car front/side (Sideswipe)	10%
	B3	Truck- car collision, oncoming traffic: Truck front vs. car side	5%
	B4	Truck- car collision, traffic ahead in same direction: Truck front vs. car rear	10%
	B5	Truck- car collision, intersection: Truck front vs. car side	15%
	B6	Truck- car collision, traffic ahead in same direction: Car front vs. truck rear	10%
	B7	Truck- car collision, intersection: Car front vs. truck side	10%
	B8	Truck- car collision, lane change accident: Truck side vs. car side	5%
Unprotected road users	C1	Truck- unprotected collision, truck front vs. unprotected when taking off	5%
	C2	Truck- unprotected collision, truck vs. unprotected when reversing	5%
	C3	Truck- unprotected collision, unprotected that suddenly crosses the direction of truck, e.g. at cross road	25%
	C4	Truck- unprotected collision, truck front/side vs. unprotected when turning	20%
	C5	Truck- unprotected collision, truck side vs. unprotected, lane driving	10%
	C6	Truck- unprotected collision, meeting accident	5%
	C7	Truck- unprotected collision, unprotected drives into truck	10%

The overall EU-28 casualty numbers (see Table 2) were determined from the Community database on Accidents on the Roads in Europe (CARE). CARE is a database that aggregates data on road accidents resulting in death or injury from European countries. The proposed change in legislation will affect the whole of the EU, which is why the analysis was based on casualty numbers from accidents occurring in any member state of EU-28 and involving at least one HGV.

A database query was performed for the number of fatally injured (at 30 days), seriously injured (at 30 days) and slightly injured.

Query filters applied were:

- EU 28 (1957 - now)
- Last year of data availability
- Transport Mode involved in accident = ‘Heavy Goods Vehicle’

For Lithuania no casualty numbers are available in the CARE database, which is why the country was omitted for this study. In the following, the term *EU-28* is to be read as *EU-28 (without Lithuania)* whenever casualty numbers are discussed. For Estonia, Finland and Italy, the database numbers for non-fatal casualties are not split into seriously or slightly injured. The average ratio between severity levels from the remaining countries was applied to produce an estimate of the numbers for these countries. This approach of averaging the biggest group available (the whole remaining EU) is considered the best possible estimate because the characteristics influencing this breakdown are potentially manifold (e.g. ratio of of urban and rural traffic, road junction layout, mix of transport modes, age structure of population, etc.) and largely unknown which prohibits a selection of any specific other country as a model.

It was not possible to form an estimate of the effectiveness of improved direct vision from a synthesis of published research; hence, STATS19 accident data was used to define an upper boundary for the estimate based on contributory factors to the accident. STATS19 is the database of all police reported injury accidents on public roads in Great Britain (GB). The information recorded for each accident includes details of the accident circumstances, contributory factors in the opinion of the police officer at the time of the accident, any vehicles involved and the resulting casualties. Average data from the years 2011–2013 was used of accidents involving an HGV (vehicle type = ‘20’ or ‘21’) and a pedestrian casualty. Only those accidents were counted, where the police attended the scene and recorded contributory factors.

Table 2: EU-28 casualties in accidents involving HGVs over 3.5 tonnes (N2/N3 vehicles) by country; numbers for 2013 or latest year available; data for Lithuania not reported; *: injury severity not reported, hence estimated ratio based on average of rest of EU (Source: CARE database)

Country	Year of data	Fatally injured	Seriously injured	Slightly injured
Austria	2012	77	303	1,236
Belgium	2013	100	359	2,326
Bulgaria	2009	179	301	596
Croatia	2013	41	105	434
Cyprus	2013	3	0	6
Czech Republic	2013	124	300	1,833
Denmark	2013	32	119	61
Estonia	2009	21	47*	201*
Finland	2013	70	89*	380*
France	2013	463	1,429	1,771
Germany	2013	759	7,031	32,956
Greece	2012	58	60	344
Hungary	2013	106	359	893
Ireland	2010	13	34	226
Italy	2013	267	1,165*	4,979*
Latvia	2013	37	44	288
Lithuania	-	-	-	-
Luxembourg	2013	8	10	26
Malta	2010	1	7	13
Netherlands	2013	83	122	310
Poland	2013	748	1,403	3,384
Portugal	2013	80	122	1,279
Romania	2013	139	264	558
Slovakia	2010	106	224	1,188
Slovenia	2012	3	22	87
Spain	2013	217	485	3,280
Sweden	2013	30	150	863
United Kingdom	2013	264	1,131	7,540
Total		**4,029**	**15,685**	**67,058**

4 CASUALTY REDUCTION POTENTIAL

This section explores the technical context of the analysed vehicle design changes regarding direct vision VRU impact performance and vehicle occupant protection, and subsequently derives for each design change the size of the target population (based on the relevant European casualty numbers) and the potential casualty reduction if it was adopted for the full HGV fleet. The results are summarised to achieve a prediction of the overall annual reduction potential in fatally and seriously injured casualties across EU-28.

4.1 EUROPEAN CASUALTY NUMBERS IN HGV ACCIDENTS

The latest available annual casualty numbers, summarised for EU-28 and split by severity and transport mode of casualty, are cited in Table 3.

Table 3: EU-28 casualties in accidents involving HGVs by transport mode; numbers for 2013 or latest year available (Source: CARE database)

Transport mode	Fatally injured	Seriously injured	Slightly injured
HGV occupants	585	3,472	14,877
LGV occupants	149	467	1,876
Car occupants	1,921	7,504	38,389
Powered two wheeler riders	309	1,286	2,944
Cyclists	285	1,196	3,694
Pedestrians	693	1,359	2,682
Other/unknown	87	401	2,596
Total	**4,029**	**15,685**	**67,058**

For easier reference the above numbers of different transport modes are further summarised into three relevant main groups (Table 4): HGV occupants; light vehicle occupants (including LGV and car occupants) and vulnerable road users (VRUs; including powered two wheeler riders, cyclists and pedestrians). These numbers form the basis of the subsequent target population estimates in the following subsections. The difference in the total casualty numbers compared to Table 3 arises from the dismissal of the non-categorised casualties (other/unknown), based on the fact that the background to these casualties is unknown and the circumstances potentially unusual so that they likely cannot be affected by the scope of the analysed vehicle design changes.

It can be seen that the largest number of casualties occurs among occupants of light vehicles (52% of fatalities), followed by VRUs (33%). Although the selection of accidents is reduced to collisions which involve at least one HGV, the occupants of the HGVs themselves only make up a minority of the casualties (15%). This gives an indication of the physical advantage in collisions provided by the size and elevated mass of HGVs.

Table 4: EU-28 casualties in accidents involving HGVs by transport mode, summarised (Source: CARE database)

Transport mode	Fatally injured	Seriously injured	Slightly injured
HGV occupants	585	3,472	14,877
Light vehicle occupants	2,070	7,971	40,265
VRUs	1,287	3,841	9,320
Total	**3,942**	**15,284**	**64,462**

4.2 DIRECT VISION

The driver’s field of view is made up of the areas that can be seen through front and side windows (direct vision) and via mirrors or other supporting devices such as cameras (indirect vision). The design freedom that would result from increased maximum cab dimensions could be used to improve the direct vision from HGV cabs. This section explains the technical context and quantifies the casualty reduction potential.

4.2.1 Improvements to direct vision

Many accidents between HGVs and VRUs occur because pedestrians or cyclists are not visible to the driver (Volvo Trucks, 2013) and could be prevented by improved direct vision to the front and to the side from the HGV driving position.

A large body of research is available on the problems regarding direct vision in conventional cab designs under the current dimension legislation, for example (Cook et al., 2011a), (Cook et al., 2011b), (Cook et al., 2011c) and (Delmonte et al., 2012). Figure 1 from Delmonte *et al.* demonstrates the extent of the problem by visualising the visibility of cyclists positioned 1 to 3 metres sideways from the cab. Through the windscreen, only cyclists 13 and 14 are entirely visible; cyclists 11 and 12 are partially visible; and cyclist 9 is partially visible, but only to a very limited extent. All other cyclists are not visible. Through the nearside window, only cyclist 7 is partially visible. All other cyclists are not visible.

With an adapted design, featuring extra glazed areas and larger windscreens and side windows that extend further down, the driver would be able to detect a larger proportion of VRUs around the vehicle who would be occluded in current cab designs. Lowering the overall position of driver and cab and thereby bringing the driver’s line of sight closer to the level of cyclists and pedestrians could also contribute to a better detection rate. To allow for this to happen, other structural parts would have to be relocated, which could be facilitated by extended cab dimensions.

Direct vision will mitigate mainly the problem of low-speed run-overs (some reports cite closing velocities of up to 20 km/h (Feist & Faßbender, 2008)) in critical situations, such as pulling away from traffic lights and turning.

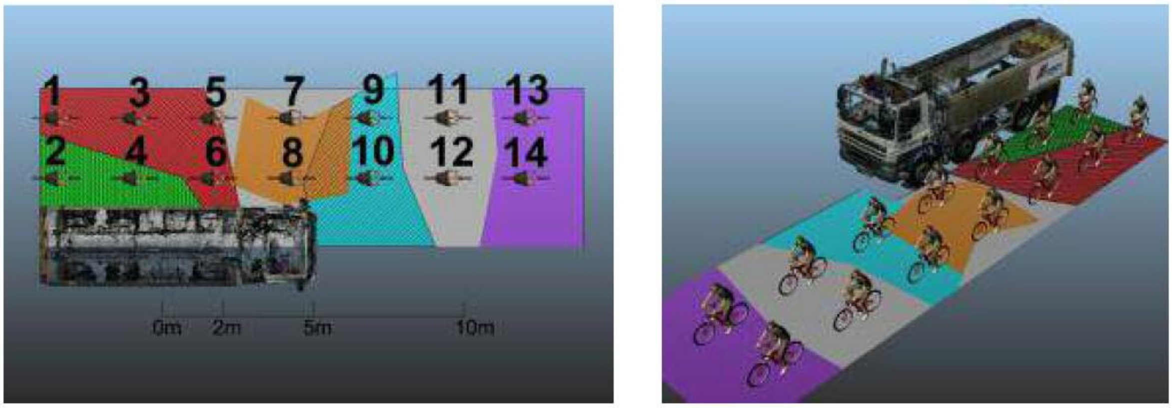

Figure 1: Visibility of cyclists from the driver's position (British right hand drive model). Ground projection of direct vision through windscreen is shown in purple; ground projection of direct vision through side window is outside of the displayed area; indirect vision through mirrors is shown in other colours. (Delmonte et al., 2012)

4.2.2 Casualty reductions by improvements to direct vision

Direct vision from HGV cabs to the front and to the side can be expected to play a major role in accident scenarios where the HGV impacts the road user in relatively low-speed situations that would allow bringing the vehicle to a halt, had the driver seen the road user. The target population for improved direct vision therefore includes accident scenarios C1 and C4 (see **Error! Reference source not found.**Table 1), which comprise about 25% of VRU casualties. Applying this proportion to the European casualty numbers from Table 4 leads to the target population estimates given in Table 5.

Table 5: EU-28 casualty target population for improved direct vision

Transport mode	Target population fatally injured	Target population seriously injured
VRUs	322	960

Research acknowledges that improved frontal and lateral direct vision is effective in preventing VRU casualties in accident scenarios such as run-overs while the HGV is pulling away or turning, or while a VRU is crossing the road in front of the HGV (Summerskill, 2011; Welfers et al., 2011; Volvo Trucks, 2013). However, no study could be identified that quantified the effectiveness of improved direct vision.

Not all casualties in these accident scenarios will be prevented by direct vision, but only those cases where the driver did look but was not able to see the hazard. Data from the STATS19 database (police-reported accidents in Great Britain) show that for about 30% of fatal and 20% of serious accidents between HGVs and pedestrians, one of the contributory factors noted by the police officer was '405 - driver failed to look properly' for the HGV driver. Because the driver failed to look these cases could most likely *not* be prevented by improved direct vision. Conversely, the remaining 70% of fatalities and 80% of seriously injured VRUs could possibly be influenced and are therefore used as an estimate of the upper boundary of the effectiveness estimate (Table 6).

The lower boundary of the effectiveness estimate has to remain of purely indicative nature because no published study is available quantifying the effects and the available STATS19 accident data lacks sufficient detail to draw firm conclusions. Accident scenario C1 involves a collision with a VRU in front of the HGV when pulling away. These cases, where VRUs move into the obscured zone in front of the HGV while it's stationary or where the HGV driver forgets VRUs on the zone during a halt, might be almost entirely avoidable if the driver had ideal direct vision to the front, because it can be assumed that the proportion of drivers who fail to check the direct sight line in front when pulling away is expected to be negligible. This accident scenario, C1, comprises 5% of VRU casualties or 25% of the above defined target population. Accident scenario C4 involves collisions of VRUs with the front *and* with the side of the HGV when turning. Although it can be reasonably expected that a certain proportion would be visible to the driver with improved direct vision to the side, it appears impossible to quantify the effect based on the available data. Therefore, as a lower boundary of effectiveness it is assumed that none of the cases of scenario C4 would be prevented. These considerations lead to the lower boundary of the estimates in Table 6.

Table 6: Estimated effectiveness of improved direct vision; numbers in brackets denoting indicative estimates based on theoretical considerations regarding collision configurations (see body of text)

Transport mode	Predicted effectiveness estimate in target population	
	Fatal	Serious
VRUs	(25%)–70%	(25%)–80%

Applying these effectiveness estimates to the target population numbers yields the following ranges of potential casualty savings across EU-28 (Table 7).

Table 7: Annual VRU casualty reduction potential for EU-28 by improved direct vision; numbers in brackets denoting indicative estimates based on theoretical considerations regarding collision configurations (see body of text)

Transport mode	Casualty saving potential, fatally injured	Casualty saving potential, seriously injured
VRUs	(81)–225	(240)–768

4.3 VRU IMPACT PERFORMANCE

The injury outcome of VRUs in collisions with HGVs is dependent on the phase of primary contact between vehicle and VRU, on the secondary contact with the road surface or road-side objects, and on whether or not a subsequent run-over occurs. All three of these phases are to a certain extent determined by the front end design of the impacting HGV. Nevertheless, the protection of VRUs in this respect is not currently covered in legislation. This section explains the technical context and quantifies the casualty reduction potential of related vehicle design changes.

4.3.1 Improvements to VRU impact performance

The project APROSYS developed a concept of a tapered front end design for HGVs (Feist & Faßbender, 2008). The ‘nose cone’ is a tapered front end structure made of foam that is intended to reduce the run-over frequency by deflecting impacted VRUs away from the vehicle to the side and also to eliminate sharp corner impacts. Figure 2 demonstrates these effects in an impact test with a pedestrian dummy.

Figure 2: APROSYS nose cone attached to an HGV front end deflecting a pedestrian dummy to the side during an impact test (Feist and Faßbender, 2008)

Based on the results from the APROSYS project, Welfers *et al.* (2011) developed a potential re-design of the front end of a tractor unit for a 40-tonne HGV making use of the design freedom that would result from increased maximum cab dimensions (Welfers et al., 2011). The design was optimised under aerodynamic considerations, so as to improve both, safety performance and fuel economy (Figure 3).

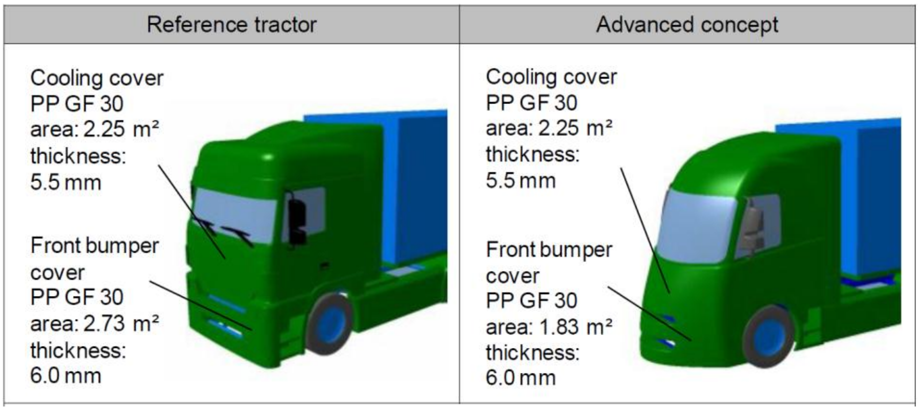

Figure 3: Tapered front end design for improved safety and aerodynamics (Welfers et al., 2011)

4.3.2 Casualty reductions by improvements to VRU impact performance

The target population amongst VRUs for a tapered front end design of HGVs consists of all accident scenarios where the road user is impacted by the front of the HGV. This applies to accident scenarios C1, C3 and C6 (see Table 1**Error! Reference source not found.**), which comprise about 35% of VRU casualties. Applying this proportion to the European casualty numbers from Table 4 leads to the target population estimates given in Table 8.

Table 8: EU-28 casualty target population for improvements to VRU impact performance (Source: CARE database)

Transport mode	Target population fatally injured	Target population seriously injured
VRUs	450	1,344

In 2010, Robinson *et al.* carried out a benefit analysis for different HGV safety measures for GB based on in-depth accident data from the Heavy Vehicle Crash Injury Study (HVCIS) database (Robinson et al., 2010). Benefits of fitting HGVs with different front end structures (length increase between 0.50 and 2.25 metres) were analysed in detail on a case-by-case basis, taking into consideration, for example, the age of casualties or the belt wearing status of car occupants. The range of the effectiveness estimate from this study for a tapered front end structure to deflect VRUs sideways is cited in Table 9.

The prospective study by Welfers *et al.* (2011) predicted potential VRU casualty savings by a tapered front end design. The estimates about the effectiveness of the front end design in preventing were based on an assumed high effectiveness at accidents below 40 km/h and markedly decreasing effectiveness at higher speeds. The estimates are cited in Table 9.

Table 9: Effectiveness estimates in published literature for tapered front end design

Transport mode	Effectiveness estimate by (Robinson et al., 2010)		Effectiveness estimates by (Welfers et al., 2011)	
	Fatal	Serious	Fatal	Serious
VRUs	29%–47%	–	42%–63%	–

For fatal casualties the two published estimates are combined by selecting the overlapping range to derive an estimated effectiveness (Table 10). No published estimates could be identified for the effectiveness in preventing seriously injured casualties. The accident scenarios selected for the target population are all cases where the front end of the HGV impacts the road user. The injury mechanisms leading to serious injuries will, therefore, fall into the same general categories as for fatal injuries: The primary impact by the HGV, the secondary impact on the road surface or with roadside objects, and potential subsequent run-over. However, the distribution amongst these is expected to be markedly different, because run-overs by HGVs can be assumed to result in fatal accidents in a disproportionately high number of cases compared to impacts without subsequent run-over. The effectiveness is therefore assumed to be markedly reduced for serious injuries. This is reflected in the present analysis by reducing the estimate for fatal injuries by half (Table 10). The high level of uncertainty of these assumptions is denoted in the table by enclosing the values in brackets.

Table 10: Estimated effectiveness of tapered front end designs amongst the target population; numbers in brackets denoting indicative estimates based on theoretical considerations regarding collision configurations (see body of text)

Transport mode	Predicted effectiveness estimate in target population	
	Fatal	Serious
VRUs	42%–47%	(21%)–(24%)

Applying these effectiveness estimates to the target population numbers yields indicative ranges of potential casualty savings across EU-28 (Table 11).

Table 11: Annual VRU casualty reduction potential for EU-28 by tapered front end designs; numbers in brackets denoting indicative estimates based on theoretical considerations regarding collision configurations (see body of text)

Transport mode	Casualty saving potential, fatally injured	Casualty saving potential, seriously injured
VRUs	189–212	(282)–(323)

4.4 VEHICLE OCCUPANT PROTECTION

Because of the high mass of HGVs, their collisions are generally characterised by a high level of kinetic energy that needs to be dissipated. In collisions with other HGVs (e.g. front-to-rear motorway accidents) this has severe implications for the safety of the occupants of the impacting HGV; in collisions with lighter vehicles such as passenger cars this mainly affects the safety of the occupants of the light vehicle. This section explains the technical context and quantifies the casualty reduction potential of related vehicle design changes.

4.4.1 Measures for improved vehicle occupant safety

Crumple zones on the vehicle front, placed at a height suitable for interaction with the rear chassis of other HGVs (typically 700–1,100 mm from the ground), can dissipate energy by deforming under load. The effectiveness of this concept is dependent on the available deformation length before the rigid passenger compartment and can, therefore, be increased by larger permissible cab dimensions (Robinson et al., 2010).

A serious issue in car-to-HGV frontal collisions is the general lack of geometric compatibility, with the passenger car being much lower in height than the HGV. Cars under-running HGVs in collisions at high closing speeds can lead to severe deformation and intrusion in the passenger compartment of the car because the main load paths cannot interact with the heavy vehicle (Gwehenberger et al., 2004). To alleviate this problem, rigid front under-run protection systems (FUPS) (typically 400-500 mm from the ground) are already a current legislative requirement for N2 and N3 vehicles. Higher compatibility and thereby better protection for the car occupants in accidents could be accomplished energy-absorbing frontal under-run protection systems (EAFUPS) designed to deform in a controlled way and absorb any residual energy that cannot be absorbed by the car's front end.

The nose cone front end structure developed by APROSYS can, for instance, be filled with energy-absorbing material of different strengths which can serve self-protection and protection of lighter vehicles' occupants (Welfers et al., 2011).

The tapered front end of the concept by Welfers *et al.* features aluminium substructures in the form of two bumper beams with crash boxes (see Figure 4).

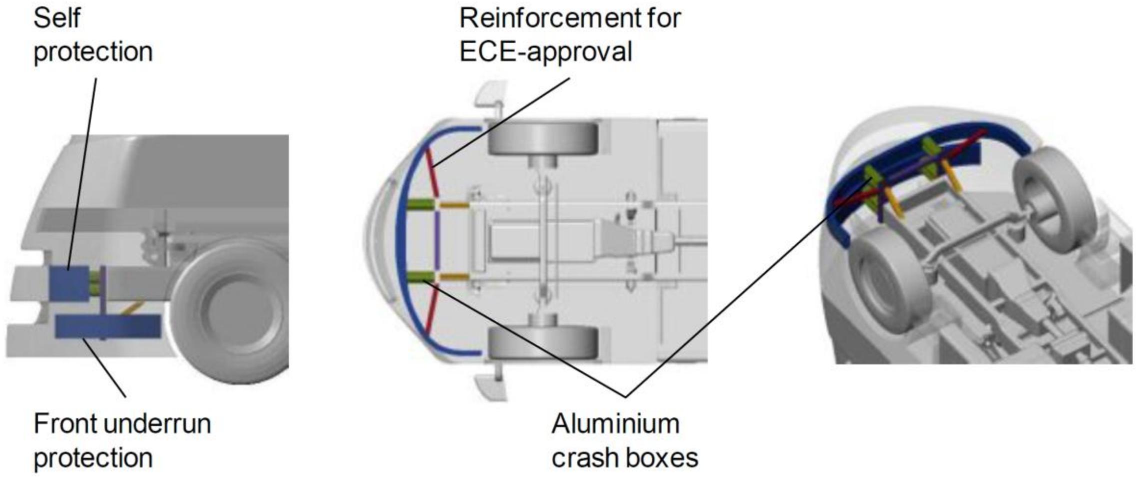

Figure 4: Crash management system of tapered front end concept (Welfers et al., 2011)

4.4.2 Casualty reductions by energy-absorbing frontal underrun protection systems and HGV crumple zones

The target population for EAFUPS and HGV crumple zones for self-protection is made up of the casualties from all accidents where the main structural interaction can be assumed to occur with the front end of the HGV. This applies to accident scenarios A1, A3, A4 and A5 (see Table 1**Error! Reference source not found.**), which account for about 70% of HGV occupant casualties, assuming that most casualties in scenario A1 occur due to impacting heavy off-road objects. Regarding collisions involving light vehicles, accident scenarios B1, B3, B4 and B5 involve the HGV front end, which account for about 65% of light vehicle occupant casualties. Applying the proportions of these accident scenarios to the European casualty numbers from Table 4 leads to the target population estimates given in Table 12.

Table 12: EU-28 casualty target population for improvements to vehicle occupant safety (Source: CARE database)

Transport mode	Target population fatally injured	Target population seriously injured
HGV occupants	410	2,430
Light vehicle occupants	1,346	5,181

The above mentioned study by Robinson *et al.* also analysed the effects of improvements to vehicle occupant safety (EAFUPS and crumple zones for self-protection). The estimated effectiveness in frontal impacts if all HGVs were equipped, based on in-depth accident data from GB, are cited in Table 13. Although HGV front to light vehicle side or rear collisions were not included in Robinson's study, it can be assumed that the energy-absorbing effect of the HGV crumple zone will also be effective in these cases, which is why they were included in the target population (scenarios B3, B4 and B5). Table 13 also summarises the effectiveness estimates by Gwehenberger *et al.* (2004) from the project VC-COMPAT. It estimated potential casualty savings through EAFUPS in frontal impacts, the baseline being HGVs equipped with rigid FUPS, which are mandatory equipment in Europe. The figures were based on a case-by-case analysis of in-depth accident data and the authors considered them conservative estimates. Welfers *et al.* (2011) did not quantify potential casualty savings among vehicle occupants.

Table 13: Effectiveness estimates in published literature for energy-absorbing frontal underrun protection (EAFUPS) and HGV crumple zone

Transport mode	Effectiveness estimate by (Robinson et al., 2010)		Effectiveness estimates by (Gwehenberger et al., 2004)	
	Fatal	Serious	Fatal	Serious
HGV occupants	12%–38%	–	–	–
Light vehicle occupants	5%–22%	–	10%–11%	30%

From these published estimates a predicted range of effectiveness is derived by selecting the overlapping ranges of estimates (where more than one estimate is available), see Table 14. For seriously injured HGV occupants, where there is no estimate available in published research, the effectiveness is assumed to be of a similar magnitude as the effectiveness for fatally injured. Therefore, the same (wide) range is applied to serious casualties. The high level of uncertainty of these assumptions is denoted in the table by enclosing the values in brackets.

Table 14: Estimated effectiveness of energy-absorbing frontal underrun protection (EAFUPS) and HGV crumple zone amongst the target population; numbers in brackets denoting indicative estimates based on theoretical considerations regarding collision configurations (see body of text)

Transport mode	Predicted effectiveness estimate in target population	
	Fatal	**Serious**
HGV occupants	12%–38%	(12%)–(38%)
Light vehicle occupants	10%–11%	30%

Applying these effectiveness estimates to the target population numbers yields the following ranges of potential casualty savings across EU-28 (Table 15).

Table 15: Annual vehicle occupant casualty reduction potential for EU-28 by energy-absorbing frontal underrun protection (EAFUPS) and HGV crumple zone; numbers in brackets denoting indicative estimates based on theoretical considerations regarding collision configurations (see body of text)

Transport mode	Casualty saving potential, fatally injured	Casualty saving potential, seriously injured
HGV occupants	49–156	(292)–(923)
Light vehicle occupants	135–148	1,554
Total	**184–304**	**1,846–2,477**

4.5 OVERALL CASUALTY REDUCTION POTENTIAL

The ranges of expected casualty reductions established in the preceding sections are summarised in Table 16 below. Note that the two casualty subgroups of VRUs affected by direct vision and VRU impact performance partially overlap. To avoid double-counting the casualty savings resulting from improved impact performance in accident scenario C1 (14.3% of potential casualties saved) were subtracted once to establish the sum in the row *VRUs*.

Table 16: Annual casualty reduction potential for EU-28 by safer front end designs for HGVs

Transport mode	**Casualty saving potential, fatally injured**	**Casualty saving potential, seriously injured**
HGV occupants	49–156	292–923
Light vehicle occupants	135–148	1,554
VRUs	243–407	482–1,045
Total number	**427–711**	**2,328–3,522**
Proportion of all EU-28 casualties involving HGVs	**11%–18%**	**15%–22%**

This reduction in casualty numbers can also be expressed as monetary societal benefits by applying average European monetary values for the prevention of road casualties, which are currently €1,564,503 per fatal casualty and €231,278 per serious casualty (European Commission, 2013b). The monetary benefits that can be expected therefore range from approximately 1.2 to 1.9 billion Euros per annum across EU-28. This sum is equivalent to about 0.6–0.9% of the estimated costs attributed to injuries in all road collisions in the EU (EU-27 numbers, year 2010), (ETSC, 2013b).

5 DISCUSSION AND CONCLUSIONS

The objective of this study was to predict the number of fatal and serious casualties among VRUs, light vehicle occupants and heavy vehicle occupants that could be avoided per year across EU-28 by HGV front end design changes, afforded by the change in the weights and dimensions legislation.

The study found that the considered design changes (improved direct vision, deflecting front end, improved and energy-absorbing front under-run protection, and crumple zones) might lead to considerable road casualty reductions and large monetary societal benefits in Europe. This makes a mandatory introduction of safer cabs before 2022 appear advisable in order to realise benefits to society as soon as possible. Design changes could also be introduced individually, because some measures such as improved direct vision might yield a high benefit while being easy to implement (technically and with regard to developing type-approval legislation).

Alongside the reduction in fatally and seriously injured road users, other societal benefits can be expected from the design changes; for example, significant fuel saving benefits because a tapered front end design allows optimising the aerodynamic performance of the vehicle (Robinson et al., 2010; Welfers et al., 2011), or monetary benefits from the reduction of damage-only accidents, such as reduced side-swipe collisions with cars due to improved lateral direct vision.

However, the casualty reduction numbers reported can only give an indication of the magnitude of the impact and should not be understood as exact measures. This is due to the following principal limitations of the approach:

The effectiveness estimates used are of a predictive nature, i.e. not based on real-world accident statistics but rather isolated trials or simulations, or pure expert judgement. This approach involves, by its nature, a high level of uncertainty but is the best available approach based on the available data, because none of the design changes are deployed to production vehicles in the fleet yet, hence no real-world data is available.

The casualty savings calculated are for an assumed 100% fleet fitment rate. Although this is, of course, not a realistic assumption for the near future because fleet dispersion would take years or decades, it is a good indicator to weigh benefits against costs when discussing safety legislation. A more detailed future analysis could take fleet dispersion into account and in particular try to also reflect general future trends in European HGV casualty numbers. For example might the future advancement of primary safety technologies, such as autonomous emergency braking (AEB), which is already mandatory for new HGVs, black spot cyclist detection, or 360° camera view and VRU avoidance, address a proportion of the reported casualties.

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6 REFERENCES

Bovenkerk J (2006). APROSYS SP2 - Strategies for enhanced pedestrian and cyclist friendly design - AP-SP21-0062. Aachen: RWTH Aachen.

Cook S, Summerskill S and Marshall R (2011a). The development of improvements to drivers' direct and indirect vision from vehicles – impact assessment. Report for Department for Transport DfT TTS Project Ref: S0906 / V8. Loughborough: Loughborough University.

Cook S, Summerskill S and Marshall R (2011b). The development of improvements to drivers' direct and indirect vision from vehicles - phase 1. Report for Department for Transport DfT TTS Project Ref: S0906 / V8. Loughborough: Loughborough University.

Cook S, Summerskill S and Marshall R (2011c). The development of improvements to drivers' direct and indirect vision from vehicles - phase 2. Report for Department for Transport DfT TTS Project Ref: S0906 / V8. Loughborough: Loughborough University.

Delmonte E, Manning J, Helman S, Basacik D, Scoons J, Chappell J et al. (2012). Construction logistics and cyclist safety - PPR639. Crowthorne: TRL Limited.

Edwards MJ, Coo Pd, Zweep Cv, Thomson R, Damm R, Martin T et al. (2007). VC-COMPAT - Final technical report. TRL/TNO.

ETSC (2013a). 7th Road Safety PIN Report. Brussels: European Transport Safety Council (ETSC).

ETSC (2013b). EU Funds for Road Safety. Multiannual Financial Framework 2014-Multiannual Financial Framework 2014-2020. Saving Lives on EU Roads until 2020. Updated July 2013. Brussels: European Transport Safety Council (ETSC).

European Commission (2013a). Impact Assessment Accompanying the document: Proposal for a Directive of the European Parliament and of the Council amending Council Directive 96/53/EC laying down for certain road vehicles circulating within the Community the maximum authorized dimension. Brussels: European Commission.

European Commission (2013b). Monetary valuation of road safety. Available at: ec.europa.eu/transport/road_safety/specialist/knowledge/measures/monetary_valuation_of_road_safety/index.htm.

European Commission (2013c). Proposal for a Directive of the European Parliament and of the council amending Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the Community the maximum authorised dimensions in national and international traff.

European Parliament (2014). Report on the proposal for a directive of the European Parliament and of the Council amending Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the Community the maximum authorised dimensions in national and inter.

Feist F and Faßbender S (2008). APROSYS SP 2 - Demonstration of truck front design improvements for vulnerable road users - AP-SP21-0088. Aachen: RWTH Aachen.

Gugler J and Feist F (2009). APROSYS SP 2 - Final report for the work on “Heavy Vehicles” (SP 2) - Deliverable report AP-SP90-0002. TUG (SPL).

Gwehenberger J, Bende J, Knight I and Klootwijk C (2004). VC-COMPAT - Collection of Existing In-depth Accident Cases and Prediction of Benefit on Having Front and Rear Underrun. GDV, Insurance Institute for Traffic Engineering.

Robinson BJ, Knight I, Robinson T, Barlow T and McCrae I (2010). Safer aerodynamic frontal structures for trucks: final report. Published Project Report PPR533. Crowthorne: TRL Ltd.

Summerskill S (2011). The identification of 'Blind Spots' in direct and indirect vision for Category N2 & N3 vehicles using Digital Human Modelling. Document GRSG-100-26.

Summerskill S and Marshall R (2014). The design of category N3 vehicles for improved driver direct vision - Final Report. Prepared for Transport & Environment / Transport for London. Loughborough: Loughborough University.

Volvo Trucks (2013). European Accident Research and Safety Report 2013. Gothenburg: Volvo Trucks.

Welfers T, Ginsberg S, Funcke M, Hamacher M, Matheis R, Wohlecker R et al. (2011). Design of a Tractor for Optimised Safety and Fuel Consumpation. Aachen: Forschungsgesellschaft Kraftfahrwesen mbH (FKA).