Study on Enhanced Truck Front End Designs (TFEDs)

Safety Benefits for Vulnerable Road Users (VRUs)

Final Report

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European Commission
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List of Key Abbreviations

Please find below a list of the key abbreviations used within this report:

CAM	Camera systems safety measure
CARE	Community database on Accidents on the Roads in Europe
CMS	Camera monitoring system
DET	Sensor-based detection systems safety measure
DIR	Direct vision safety measure
DVS	Direct vision standard
EC	European Commission
EU	European Union
FUP	Front underrun protection safety measure
HGV	Heavy goods vehicle
HVAI	Heavy vehicle aggressivity index
IDV	Indirect vision safety measure
LEC	Low-entry cab
KSI	Killed or seriously injured
TFED	Truck front end design
VAB	Vulnerable road user airbag
VIP	Vulnerable road user impact protection
VRU	Vulnerable road user

1 Executive Summary

In 2014 there were over 3,850 reported road fatalities across the EU 28 countries due to collisions involving heavy goods vehicles (HGVs) of >3.5 tonnes, accounting for 15% of all such fatalities (ERSO, 2016). Passenger car occupants were the most common fatality in collisions involving HGVs, accounting for almost half of all reported road fatalities. Pedestrians and pedal cyclists, when considered together, were the next most common fatality in a HGV collision (~25%), whilst just over 10% of fatalities resulting from HGV collision were HGV occupants themselves.

When compared to car occupants, however, it is evident that both pedestrians and pedal cyclists are at greater risk of more severe injuries during collisions with HGVs. Where the injury severity for casualties involved in collisions with HGVs were reported by the European CARE database, pedestrians were found to have the greatest proportion of killed and seriously injured (KSI) casualties (>40%). Pedal cyclists had the next largest proportion of KSIs (~35%), whilst car occupants had the greatest proportion of slight injuries (>70%). This imbalance in the distribution of injury severities among pedestrians and cyclists, in comparison to car occupants, has led to calls to better protect these vulnerable road users (VRUs) during HGV collisions.

Current traditional European HGV designs primarily employ cab-over-engine tractor unit configurations to maximise the commercial loading space within the current dimensions permitted by Council Directive 96/53/EC. The tightly packaged design promoted by this Directive does not encourage adequate space for suitable crumple zones to protect other road users, whilst its cuboid cab design, coupled with a high driver position, increases the difficulty of detecting VRUs, especially on the nearside (passenger side) of the vehicle.

Directive (EU) 2015/719 (which amends 96/53/EC) provides HGV cab length derogations that allow manufacturers to design extended cabs (or enhanced truck front end designs (TFED)), as long as the additional length is not used to increase load carrying capacities. These derogations are only permitted, however, if the new design improves the safety of the HGV for other road users, driver comfort and the aerodynamic efficiency of the HGV. Through this, the Directive aims to encourage improvements in HGV designs, without the economic disbenefits associated with a reduction in commercial load carrying capacity. Importantly, for this project, these aerodynamic improvements must be supported by an improvement in HGV safety, with this focussing in particular on better VRU detection and mitigating the severity of damage or injuries caused to other road users.

The approach proposed by Directive 2015/719 permits cab length derogations based on requirements to implement a specific cluster of regulated safety measures. The particular safety measures proposed for clustering by the European Commission included regulating improvements to the direct vision, indirect vision, VRU impact protection, front underrun protection and VRU airbag performance of enhanced TFEDs, in addition to considering the effects of primary active safety systems. The effect of clustering these solutions and technologies remains unknown, however, with some solutions potentially complimenting each other to result in a combined package that is more cost-effective than the sum of its component parts and others resulting in overlapping benefits where costs could be incurred more than once for the same potential benefit.

The principal aim of this project was to support the technical requirements for Directive (EU) 2015/719 that enhance vulnerable road user (VRU) and passenger car occupant safety through enhanced truck front end designs (TFEDs); in particular focussing on the cab length derogation opportunities provided through the Directive. The scope of the research included prioritising how VRU and car occupant fatalities and casualties can be prevented, or injuries mitigated, by potential regulatory changes to the requirements for the most cost-effective cluster of the five investigated safety measures.

This project was therefore the first to evaluate the cost-effectiveness of a range of clustered safety measures for improving vulnerable road user (VRU) and car occupant protection via the HGV cab length derogations proposed in Directive (EU) 2015/719. The project performed a state-of-the-art review of exemplar and conceptual technologies relevant to HGVs with enhanced TFEDs. This was followed by a systematic review and critical appraisal of the literature to establish relevant target populations, effectiveness values and costs associated with each safety measure. The effects of clustering both the casualty reducing benefits and production related costs were then calculated for a total of 63 safety measure clusters, with the benefit-cost ratios of each individual safety measure and safety measure cluster ranked in order of cost-effectiveness. This was performed for two different approaches based on two separate fleet penetration models for enhanced TFEDs. These were a "uniform" approach, which assumed equal uptake across all HGV applications and vehicle types, and a "differentiated" approach, which assumed that articulated HGVs in long haulage operations would be the only sector to adopt cab length derogations. Finally, the potential regulatory options available for each individual safety measure were considered alongside the potential benefits and limitations of each option.

The benefit-cost ratios of all individual and clustered safety measures associated with the differentiated approach were found to be considerably lower than their equivalent values for the uniform approach. When considering the uniform approach a total of three individual safety measures were observed to be cost-effective (benefit-cost ratio ranges of >1), whilst a further five safety measure clusters were also found to be cost-effective (Table 1). When considering the differentiated approach, however, only a single safety measure, for front underrun protection (FUP), was observed to be cost-effective. For the uniform approach, the highest ranked cluster was found to be the sensor-based detection system safety measure. This was closely followed up by both a combination of the detection system and FUP safety measures and the FUP safety measure on its own, both of which may prevent a considerably larger proportion of killed or serious injuries.

Table 1: Top ten ranked safety measure clusters for the uniform approach

Rank	DIR	CAM	DET	VIP	FUP	VAB	Benefit-Cost Ratio	KSI Reduction
1			✓				**1.40-2.47**	201-322
2			✓		✓		**1.25-3.62**	939-1964
3					✓		**1.16-4.39**	738-1643
4				✓			**1.10-2.37**	497-756
5			✓	✓			**1.09-2.19**	658-989
6	✓				✓		**1.04-3.32**	982-2282
7			✓	✓	✓		**1.04-2.75**	1072-2230
8			✓		✓	✓	**1.00-3.03**	1088-2315
9	✓		✓		✓		*0.99-2.75*	1096-2381
10	✓			✓			*0.99-2.19*	680-1200

Despite these significant outcomes, there were several limitations that could potentially affect the applicability and generalisability of these results. Firstly, although this project used, as best it could, an evidence base established on the current state-of-the-art in the research literature, a number of assumptions were made due to the paucity of relevant information. Key assumptions involved simplifying the benefit-cost analysis to discount the temporal trends associated with the HGV fleet, collision landscape and costs over the 10-year analysis period, the simplification of collision underreporting factors for the CARE database, the mapping of target populations between the safety measures in the same cluster, the exclusion of slight injuries, the assumption that all casualties are avoided rather than mitigated and the assumptions made when estimating the effectiveness of each safety measure.

This project further identified the regulatory options available to all safety measures. For each safety measure, all regulatory and standardised testing and assessment protocols underpinning each safety measure were considered to understand the changes needed to ensure the relevance of future regulatory requirements to HGVs with enhanced TFEDs. These concluded that the indirect vision and front underrun protection safety measures would require an update of the existing regulations (Regulations 46 and 93), whilst the remaining measures would require the development of new regulations adapted from the standardised protocols proposed within the HGV Direct Vision Standard (DVS) and Heavy Vehicles Aggressivity Index (HVAI) protocols.

Finally, the areas where further research should be performed to confirm the values used in this project were also identified. As a large proportion of effectiveness values were not based upon empirical evidence specific to the differences in performances between HGVs with regulated and unregulated TFEDs, primarily due to a paucity of research, the overall effectiveness values used within this project require confirmation. The costs used in this project were similarly affected, with further confirmation required for the cost ranges of each individual and clustered safety measure via industry stakeholder consultation. The target populations used by this project were less affected, but further research should be performed to evaluate the differences in outcome related to the differentiated approach.

2 Introduction

2.1 A European Road Safety Problem

In 2014 there were over 3,850 reported road fatalities across the EU 28 countries[1] due to collisions involving heavy goods vehicles (HGVs) of >3.5 tonnes, accounting for 15% of all such fatalities (ERSO, 2016). Passenger car occupants were the most common fatality in collisions involving HGVs, accounting for almost half of all reported road fatalities (Figure 1). Pedestrians and pedal cyclists, when considered together, were the next most common fatality in a HGV collision (~25%), whilst just over 10% of fatalities resulting from HGV collision were the HGV occupants themselves

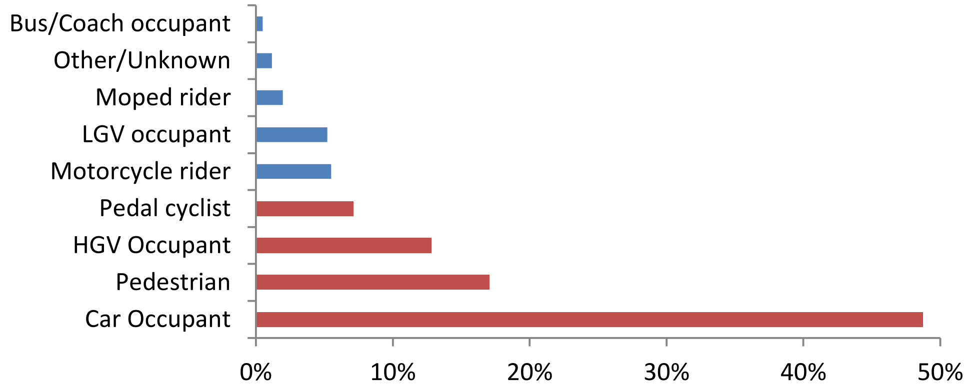


Figure 1: Distribution of reported fatalities due to collisions involving HGVs by road user type in the EU 28 during 2014 (or latest available year) (ERSO, 2016).

A similar trend was also observed for injured casualties involved in HGV related collisions. Car occupants accounted for the majority of all reported road injury casualties, with over 36,700 injuries reported across the EU 25[2] countries during 2015 (CARE database, data available in April 2017). Pedal cyclists and pedestrians were less frequently injured, with 2,818 pedal cyclist and 2,620 pedestrian casualties reported as being injured during this particular period. When combined together, however, these particular road users were, again, the next most frequently injured casualties during collisions involving a HGV.

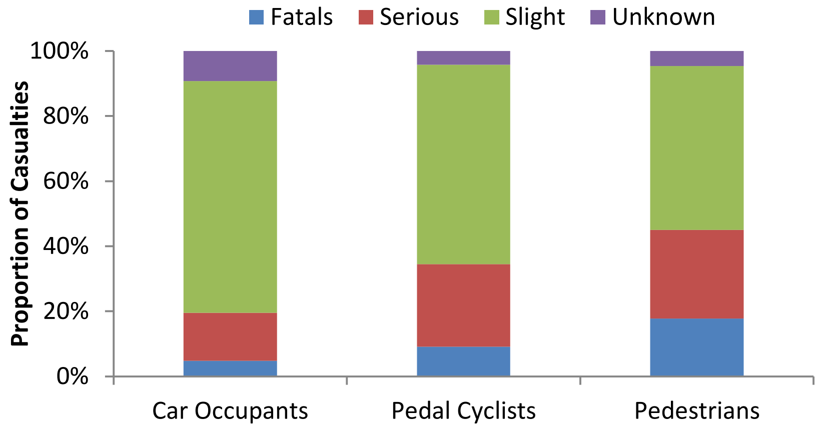


Figure 2: Proportion of all reported injured casualties involved in collisions with HGVs by road user type and injury severity in EU 25 during 2015 (CARE database, data available in April 2017).

When compared to car occupants, however, it is evident that both pedestrians and pedal cyclists are at greater risk of more severe injuries during collisions with HGVs (Figure 2). Where the severity of injury for casualties involved in collisions with HGVs were reported

[1] EU 28 countries: AT, BE, BG, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SE, SI, SK, UK.
[2] EU 25 countries: AT, BE, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, NL, PL, PT, RO, SE, SI, SK, UK.

across the EU 25 countries during 2015, pedestrians were observed to have the greatest proportion of fatalities and seriously injured casualties (>40%). Pedal cyclists had the next largest proportion of fatalities and serious injuries (~35%), whilst car occupants had the greatest proportion of slight injuries (>70%). This imbalance in the distribution of injury severities amongst pedestrians and cyclists, in comparison to car occupants, has led to calls to better protect these vulnerable road users (VRUs) during HGV collisions.

2.2 The Research Context

Current traditional European HGV designs primarily employ cab-over-engine tractor unit configurations to maximise the commercial loading space within the current dimensions permitted by Council Directive 96/53/EC. The shorter cab designs encouraged by this Directive are typified by the front of the vehicle being shaped as a flat, vertical plane, where the driver sits directly above the engine and the trailer extends toward the most rearmost aspect of the HGV to optimise the load space.

Although this optimised design may improve environmental impacts, driver comfort and safety by minimising the number of journeys made, this design does lead to sub-optimal performance per HGV-km travelled (Welfers *et al.*, 2011). The tightly packaged design promoted by 96/53/EC does not encourage adequate space for suitable crumple zones to protect other road users, whilst its cuboid cab design, coupled with a high driver position, increases the difficulty of detecting VRUs, especially on the nearside (passenger side) of the vehicle. As a result of this, HGVs that operate within urban settings may require up to six mirrors. Scanning these may take a HGV driver between four to six seconds (Cook *et al.*, 2011a), during which the immediate situation may have changed several times, thus increasing the risks of serious or fatal collisions occurring between VRUs and HGVs.

Directive (EU) 2015/719 (which amends 96/53/EC) provides HGV cab length derogations that allow manufacturers to design extended cabs (or enhanced truck front end designs (TFED)), as long as the additional length is not used to increase load carrying capacities. These derogations are only permitted, however, if the new design improves the safety of the HGV for other road users, driver comfort and the aerodynamic efficiency of the HGV. Through this, the Directive aims to encourage improvements in HGV designs, without the economic disbenefits associated with a reduction in commercial load carrying capacity. Importantly, for this project, these aerodynamic improvements must be supported by an improvement in HGV safety, with this focussing in particular on better VRU detection and mitigating the severity of damage or injuries caused to other road users.

The safety of VRUs and other road users in HGV collisions is a complex, multi-layered, issue that remains at the forefront of HGV safety research. Each phase of a HGV collision offers a unique opportunity to intervene and either prevent the collision from occurring or mitigate the consequences of such a collision. Thus, to improve the safety of HGVs with an enhanced TFED, a holistic approach must be taken towards improving safety across all the collision phases.

The holistic approach proposed by Directive 2015/719 permitted cab length derogations based on a requirement to implement a specific cluster of regulated safety measures (see Section 2.3). The particular safety measures proposed for clustering by the Commission included regulating improvements to direct vision, indirect vision, VRU impact protection, front underrun protection and VRU airbag performance of enhanced TFEDs, in addition to considering the effects of integrating primary active safety systems.

Each of these safety measures are associated with a particular phase of the collision, with each measure also typically underpinned by a range of design solutions or commercially available technologies. These solutions and technologies are, however, highly specific to the particular collision scenarios they were designed for and can often range significantly in effectiveness. Furthermore, the effect of clustering these solutions and technologies remains unknown, with some solutions potentially complimenting each other to result in a combined package that is more cost-effective than the sum of its component parts and others resulting in overlapping benefits where costs could be incurred more than once for the same potential benefit. To date, however, no investigation has been performed into understanding which clusters of safety measures would be most cost-effective for the European Union.

2.3 Aims & Objectives

The principal aim of this project was to support the technical requirements for Directive (EU) 2015/719 that enhance vulnerable road user (VRU) and passenger car occupant safety through enhanced truck front end designs (TFEDs); in particular focussing on the cab length derogation opportunities provided through the Directive.

The scope of the research included prioritising how VRU and car occupant fatalities and casualties can be prevented, or injuries mitigated, by potential regulatory changes to the requirements for the five safety measures associated with HGVs (N2 and N3).

To achieve these aims, this project sought to perform the following objectives:

- A state-of-the-art technology review of exemplar and conceptual enhanced TFEDs to determine the current technological capabilities of the industry
- A systematic review and critical appraisal of EU accidentology literature to establish target population data for HGV-to-VRU and HGV-to-car collisions and determine the current design priorities for each safety measure associated with enhanced TFEDs
- A systematic review and critical appraisal of EU research literature to establish the effectiveness and costs of specific technologies associated with each safety measure
- An analysis of safety measure clustering strategies to determine and prioritise the benefit-cost ratios associated with each combination of safety measures
- Develop regulatory options for regulating the minimum performance levels for both individual and clustered safety measures implemented on HGVs with enhanced TFEDs

2.4 Safety Measures Considered

The safety measures that were considered for review by this project were defined by the European Commission. These safety measures were to be considered for implementation on N2 and N3 vehicles with enhanced TFEDs. The five safety measures included within the scope of this project are therefore outlined below in Figure 3.

Direct Vision [DIR]

The direct vision safety measure considered within this project concerns the field of vision available for directly observing and detecting the presence of "at risk" VRUs and other road vehicles through the glazed areas of the HGV.

Indirect Vision [IDV]

The indirect vision safety measure considered within this project concerns the field of vision available for indirectly observing and detecting the presence of "at risk" VRUs in close proximity to the HGV via assistive devices. It is anticipated that these will exist as passive camera systems [CAM] and sensor-based detection systems [DET]. For clarity, sensor-based detection systems are limited to ultrasonic sensor driver warning systems.

VRU Impact Protection [VIP]

The VRU impact protection safety measure considered by this project concerns the structural components, excluding the front underrun protection (FUP) system, located at the front end of the HGV that optimises opponent compatibility and prevent run over events during frontal collisions involving VRUs.

Front Underrun Protection [FUP]

The front underrun protection safety measure considered within this project concerns the structural components located at the front end of the HGV that optimises opponent compatibility, prevents underrun events and ensures the occupant survival space during frontal collisions involving passenger cars.

VRU Airbag [VAB]

The vulnerable road user airbag safety measure considered by this project concerns the assistive device that detects or predicts the occurrence of a VRU collision to trigger and deploy an airbag to protect VRUs during impact.

Figure 3: Overview of five safety measures considered for review

These five safety measures were also considered in the context of the technological and regulatory advances currently being realised in primary active safety systems, such as autonomous emergency braking and lane keep assist, which intervene to manoeuvre the HGV. The interaction of these five measures with primary active safety measures through clustering the target populations was therefore also separately considered.

2.5 Safety Measure Clustering

When considering the implementation of five different safety measures, it is evident that there will be overlaps in the casualty groups addressed by individual measures and that there is the potential to share components between measures. The former needs to be considered in an impact assessment to avoid overestimating the benefits (each casualty can only be counted once); the latter to avoid overestimating the costs (if hardware can fulfil multiple functions). Modelling these interactions can be complex due to the number of measures that would be concurrently implemented, paired with current limitations in the availability of relevant collision statistics and costing data.

Seidl *et al.* (2017), on behalf of the European Commission (EC), developed an approach that organised the safety measures in groups to take into account their interactions when all or a subset of measures are implemented. The measures were organised in 'clusters' based on the vehicle category (i.e. where the development effort and costs are accrued and where the benefits also arise). Within each cluster, these measures are further organised into three 'layers', based on the phase of the collision in which they intend to protect the VRU or car occupant:

- Driver Assistance (permanent/continuous collision mitigation)
- Active Safety (mitigation immediately pre-collision)
- Passive Safety (protection during collision)

Using the general structure proposed by Seidl *et al.* (2017), the interactions between the five safety measures investigated by this project are illustrated by the darker blue boxes in Figure 4 below. The light blue boxes with dashed lines highlight other safety measures, not considered as part of this project (but were considered by the General Safety Review project) which may also influence the outcomes of the target population and technology clustering (further information provided in Figure 7 and Figure 8 of Seidl *et al.* (2017)).

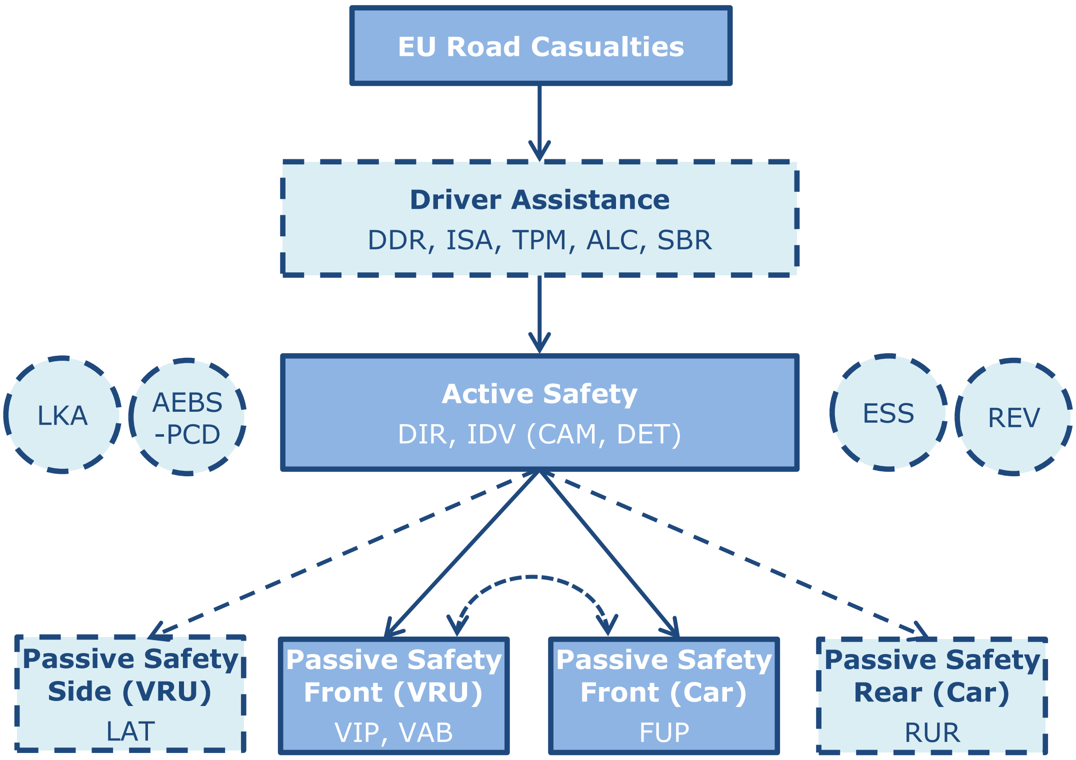


Figure 4: Modelling the interaction of the safety measures considered for implementation on enhanced truck front end designs

Whilst the initial target population for these clustered measures should be all relevant EU road casualties, each 'layer' will prevent a certain proportion of casualties, thus reducing the target population for the next layer. Although safety measure interactions within each layer are (generally speaking) expected to be limited (Seidl *et al.*, 2017), this project will consider several different clustering strategies for these safety measures (e.g. clustering between and within layers). These clustered measures will then be used to summarise the evidence bases currently underpinning the different potential policy options.

It is clear from Figure 4 that there are many safety measures under consideration by the European Commission that are focussed on protecting VRUs and passenger car occupants during HGV collision. It is also clear that these safety measures all interact considerably. The scope of this specific project, however, was to consider the clustering of the five key safety measures specified by the European Commission and defined previously in Section 2.3. Despite this, the possible interactions with the safety measures under consideration in the General Safety Review will also be briefly discussed.

When considering the five key safety measures, Figure 4 also illustrates that this project investigated active and passive safety measures only. The potential influence of these safety measures on each other is clear, with active safety measures such as direct vision and indirect vision systems (cameras and sensor-based detection systems) affecting the target populations for both the passive safety measures and each other, despite not sharing technologies. It is clear that the passive safety measures were also influenced by each other, with all forms of passive safety potentially influencing the target populations and technology effectiveness of other passive safety systems.

Please note, in accordance with Seidl *et al.* (2017), the clustering of target populations, effectiveness and costs between safety measures were mapped as precisely as possible. It must be noted that the limitations of available collision statistics did not always allow for precisely mapping layers onto each other; however, it was possible to quantitatively estimate target populations to prevent the double-counting of injured casualties. When calculating the costs associated with different technology clustering strategies, the costs were assumed equally apportioned among the safety measures sharing that cluster.

Clustered safety measures in an example collision scenario:

Consider a specific scenario where a pedestrian, in close proximity to a stationary HGV, crosses in front of the HGV as the HGV moves off. In this situation, a driver assistance safety measure could potentially help (e.g. driver distraction monitors, intelligent speed assist), although analysis of this is out of scope for this project due to uncertainty over which measures will be mandated. When considering the active safety level, however, it is clear that improved direct vision, alongside cameras and detection systems, all have the potential to prevent the collision from occurring. As all these safety measures have different effectiveness levels, a certain proportion of these collisions will still occur. Other active measures, such as Autonomous Emergency Braking for Pedestrians/Cyclists, could also influence this target population. When considering the passive safety level, however, frontal impact compatibility, front underrun protection and VRU airbags all could mitigate the severity of the collision. Again, as the technologies behind these safety measures all have different effectiveness levels, not all injuries can be mitigated through these safety measures. The overall casualty saving benefit of any particular cluster will be calculated from the remaining casualties, whilst any cost saving benefits that may be realised with the sharing of the technologies used by various safety measures will also be included.

2.6 Evaluating Outcomes

A number of key evaluation outcomes may be determined for each safety measure and each safety measure cluster reviewed by this report. These outcomes include estimating values for the target population, effectiveness, cost per vehicle, total fleet cost, casualty reduction, monetised casualty benefit, break-even cost and benefit-cost ratio associated with each safety measure or cluster. The theory behind calculating these outcome values is therefore covered in the following paragraphs.

Target populations represent the total number of fatalities and/or injured casualties that a particular safety measure or safety measure cluster is designed to prevent or mitigate each year. Target populations were calculated for each population category (pedestrians, cyclists and car occupants) and each injury severity level (fatalities and serious injuries) by uplifting EU 25 casualty data from the CARE database by 1.02 and multiplying these casualty numbers by the proportion of casualties that are relevant to the particular safety measure to be reviewed (Equation 1).

$$Target\ Population = 1.02 \times No.of\ Casualties \times Proportion\ of\ Relevant\ Casualties$$ (Equation 1)

Slight injuries were excluded from the analysis due to uncertainties around the reporting of these figures within the CARE database and the paucity of a supporting evidence base for determining the effectiveness of all safety measures. An uplift value of 1.02 was also applied to correct for the underreporting of road collisions by the CARE database. Despite this value being based on the recommendations of the HEATCO project (IER, 2006), only the uplift value associated with fatal casualties was applied. This was due to the authors' view that the majority of HGV collisions resulting in a serious injury would be attended by police and emergency services due to the perceived severity of collisions with HGVs. The uplift values for HGV collisions involving seriously injured pedestrians, cyclists and car occupants was therefore assumed to be equivalent to that for fatal collisions (i.e. 1.02).

The effectiveness of a safety measure is determined by how well the particular safety measure works. Estimates of effectiveness may be calculated based on the percentage of casualties whose death or injury could have been prevented, or injury severity mitigated, should the particular safety measure be implemented. Given the variety of research that has been performed across the five safety measures, and the range of different methods and outcomes that would be associated with these research studies, overall effectiveness values were calculated by combining the effectiveness values associated with a number of percentage based factors. These factors included the sensor activation, driver reaction and coverage factors (Equation 2), although not all safety measures investigated in this report required the application of all these factors (further information in Annex 1.4).

$$Overall\ Effectiivesness = Effectiveness\ \times Sensor\ Activation\ Factor \times Driver\ Reaction\ Factor \times Coverage\ Factor$$ (Equation 2)

When considering the cost based outcomes, both the cost per vehicle and total fleet costs were calculated for each safety measure. These were based on the estimated increase in costs related to the extra costs associated with regulating the particular safety measure, or cluster of safety measures, on HGVs with enhanced TFEDs. No estimates were made for evaluating the differences in operational costs. The costs per vehicle were calculated from information abstracted from the literature and manufacturer websites (Annex 1.5), whilst total fleet costs were calculated by multiplying these values by the total fleet size (Equation 3). The total fleet size of in use HGVs (6,442,647 HGVs) was abstracted from the ANFAC report on the size of the European motor vehicle parc in 2014 (ANFAC, 2014).

$$Total\ Fleet\ Cost = Cost\ per\ Vehicle \times Total\ Fleet\ Size$$ (Equation 3)

Annual casualty reduction benefits were then calculated by multiplying the target population and overall effectiveness values together (Equation 4). It must be noted, at this point, that this project did not cascade the casualties through the injury severity levels. This means that each casualty reduction was assumed to have been avoided rather than just mitigated. The primary reason for this was the paucity of relevant information for assisting with deciding on reassigning the injury severity levels.

$$Casualty\ Reduction\ = Target\ Population \times Overall\ Effectiveness$$ (Equation 4)

These values were then monetised to provide an estimate of the monetary benefits of the casualty reductions to the EU using the casualty prevention values calculated by Hynd *et al.* (2015), and adopted by Seidl *et al.* (2017). For the purposes of this report, collisions resulting in a fatal injury were assigned a value of €1 564 503, whilst collisions resulting in serious injuries were assigned a value of €231 278.

Finally, break-even costs and benefit-cost ratios were calculated for a 10-year evaluation period by combining values from the costs and monetised benefits. A 10-year period was selected to ensure that the one-off costs per vehicle were combined with the casualty reduction benefits associated with the estimated operational lifetime of the vehicle. This 10-year period was selected using a combination of expert opinion, with UK Department for Transport statistics showing that the largest proportion of licenced HGVs were aged between 6-13 years (32.3%) when considering years since first registration (DfT, 2016). The break-even costs describe the highest tolerable costs per vehicle for the fitment of a safety measure or safety measure cluster to remain cost-effective for society. These were calculated by normalising the monetised casualty reduction benefits by the total fleet size (Equation 5). This value can be a useful indicator when no cost estimates are available, or there is low confidence in the costs inputs, with higher break-even costs indicating a greater potential for cost-effectiveness.

$$Break\ Even\ Cost = Monetised\ Casualty\ Reduction / Total\ Fleet\ Size \quad \text{(Equation 5)}$$

Benefit-cost ratios describe the ratio of expected benefits to society (arising from the prevented casualties) to the expected costs (arising from fitment to vehicles) (Equation 6). This was calculated by taking the ratio of the casualty reduction benefits per vehicle to the costs per vehicle. As a range of estimated benefits and costs have been calculated, the greatest possible benefit-cost ratio range was estimated by comparing the maximum costs against the minimum benefits, and vice versa. Benefit-cost ratios greater than one indicate that the value of the benefits would exceed the costs and so the measure may be cost-effective, with higher benefit-cost ratios indicating higher cost-effectiveness.

$$Benefit\ Cost\ Ratio = \frac{Monetised\ Casualty\ Reduction / Total\ Fleet\ Size}{Cost\ per\ Vehicle} \quad \text{(Equation 6)}$$

It is important to note that the calculation of the break-even costs and benefit-cost ratios is based on an assumption that the safety measure, or safety measure cluster, has 100% fleet penetration and that the costs are all invested over the course of the first year. In reality, investments, and thus costs, are likely to be spread over the course of a number of years, whilst fleet penetration is also likely to vary over time. Assessing these values based on a more in-depth impact analyses is, however, beyond the scope of this project.

Finally, it has been noted that manufacturers of long-distance haulage solutions, such as articulated HGVs, may be more incentivised to apply for cab length exemptions based on the expected operational benefits from HGVs with enhanced TFEDs. This may mean that articulated HGVs, involved in long-distance haulage operations, are more likely to adopt enhanced TFEDs than other HGVs, such as rigid-body trucks, that are primarily involved in regional distribution applications (Wismans, 2016).

It is, therefore, also important to investigate the effect of a differentiated approach to the fleet penetration of each safety measure and safety measure cluster within the EU fleet. When considering the types of HGV involved in long-distance haulage, it is clear that the HGV types principally involved in this application tend to be articulated HGVs. Articulated HGVs are, however, generally recognised as having significant differences between the proportion of articulated HGVs involved in collisions with pedestrians, pedal cyclists and car occupants and the proportion of articulated HGVs in the EU HGV parc.

To assess the effects of this differentiated approach to the fleet penetration of enhanced TFEDs, the number and proportion of articulated HGVs in the EU 27 were calculated to be 3,507,849 and 57%. These figures used a combination of the Eurostat database, which provides counts of registered HGV tractor units across the EU 27 (Eurostat, 2017), and the ANFAC report on the size of the European motor vehicle parc in 2014 (ANFAC, 2014), providing the total fleet size of "in use" HGVs. To assess the effects of this differentiated approach on collision rates, the proportion of collisions involving articulated HGVs were estimated for each target population to be approximately 30% of all HGV collisions for pedestrians and pedal cyclists and 50% for car occupants across all injury severity levels. These values were approximated based on data from Bálint *et al.* (2014), which reported the proportion of KSI casualties associated with HGVs of 12-18.75 m (a proxy measure for articulated HGVs) and ≤12 m (a proxy measure for rigid-body HGVs) in length. These values were then confirmed by an analysis of Stats 19 data, comparing the number of KSI casualties for each target population and categorising these by HGV type.

Outcomes for the differentiated and uniform approaches were calculated for the target populations, costs per vehicle, total fleet costs, casualty reductions, monetised casualty benefits, break-even costs and benefit-cost ratios associated with each safety measure or cluster.

2.7 Reporting Structure

The main body of this report is comprised of ten Sections that provide an introduction to, summary of and conclusions from, the individual and clustered safety measures reviewed during this project. Following these ten Sections are three key Annexes, which provide greater detail on the evidence underpinning the preceding sections and how this evidence was collected.

The report first provides an overview of its rationale, aims, methods and outcomes in the Executive Summary, before providing greater detail on the rationale of the research in the Introduction. These are followed by five Sections providing stand-alone, high-level, summaries for each safety measure considered in this project and a further Section that considers the potential influence of active safety measures (which was considered outside the scope of this project). The ninth, and perhaps most important, Section discusses the clustering of the safety measures, whilst the final Section summarises the outcomes and conclusions of the project.

Each summary report provides readers with an overview of the technical considerations associated with implementing the safety measure, or safety measure cluster, on HGVs with an enhanced TFED. This provides a brief background on the safety measure, whilst identifying potential design opportunities for integrating the safety measure in enhanced TFEDs and any overlaps in benefits and technologies with other safety measures. These summary reports will then provide a concise summary of the target populations, overall effectiveness and costs associated with each safety measure, whilst also discussing the benefits and limitations of the evidence underpinning this data. Finally, these summary reports will highlight the key considerations that should be taken into account by policy makers if regulating the safety measure or safety measure cluster.

When considering the Annexes, Annex 1 summarises the systematic review and critical appraisal of EU accidentology literature to establish target population data for HGV-to-VRU and HGV-to-car collisions. Annex 1 further provides a systematic review and critical appraisal of research literature to establish the effectiveness and costs of the devices and design solutions associated with each safety measure. Annex 2 provides a detailed review of the options available for regulating individual or clustered safety measures on HGVs with enhanced TFEDs. Finally, Annex 3 provides a state-of-the-art technological review of the exemplar and conceptual devices and design solutions that could be applied to HGVs with enhanced TFEDs.

3 Direct Vision

3.1 Technical Considerations

3.1.1 Background on safety measure

Direct Vision [DIR]

The direct vision safety measure considered within this project concerns the field of vision available for directly observing and detecting the presence of "at risk" VRUs and other road vehicles through the glazed areas of the HGV.

HGV blind spots have long been recognised as a significant contributory factor for serious collisions with VRUs such as pedestrians and cyclists (Smith, 2008;Cook *et al.*, 2010). Up to six mirrors, along with other field of view aids, are already required to improve the driver's view of blind spots (UNECE, 2016). These measures, however, rely on the driver looking at a device at the right time to successfully prevent collisions with "at risk" VRUs, whilst concerns have been raised that further increases in the number of devices could overload drivers during critical manoeuvres (Milner and Western-Williams, 2016).

Viewing VRUs directly through the HGV windows is also likely to have several advantages over indirectly viewing them through the mirrors or camera monitors (Cook *et al.*, 2011a). Images are full size and free from distortions, whilst substantial VRU movements may be visible to attract the attention of the driver and direct eye contact may be made between both parties (Milner and Western-Williams, 2016).

Detailed direct vision requirements for HGVs are, however, yet to be technically defined. Although regulations exist to define minimum direct vision standards for passenger cars, only the recent Transport for London (TfL) HGV Direct Vision Standard, which is currently still under development, has objectively assessed the direct vision performance of HGVs (Robinson *et al.*, 2016). The proposed Direct Vision Standard (DVS) uses a simple star rating scheme to provide an objective measure of the extent a driver can potentially see from their cab directly through the windows. Visibility assessment zones alongside, and in-front of, the HGV are weighted according to the areas of greatest risks for VRUs, with a combined star rating score calculated for each HGV cab configuration (with further information provided in 0). For the purposes of this report, therefore, the direct vision safety measure is considered to be equivalent to that defined by the HGV DVS.

3.1.2 Opportunities for enhanced TFEDs

Current industry practice around designing high-visibility HGV cabs focuses on Low-Entry Cabs (LECs). Although LECs have been on the roads for several decades, their potential safety benefits from a direct vision performance perspective have only recently been fully appreciated (Robinson *et al.*, 2016). LECs primarily improve direct vision performance by reducing the cab height, reducing A-pillar profiles and increasing the number and area of the glazed areas. This was observed to result in a significant improvement in direct vision performance, with an exemplar LEC achieving a 5 star direct vision performance rating score when compared to exemplar N3 articulated (3 stars), N3 rigid (2 stars) and N3G (0 stars) vehicles (Robinson *et al.*, 2016).

Various proposals for enhanced TFEDs have, however, been shown to further improve the extent that drivers are able to view the areas surrounding the HGV. In a computational modelling study, Summerskill *et al.* (2014) investigated the effects of a number of HGV cab design iterations based on the enhanced TFED concept proposed by FKA in Welfers *et al.* (2011) (Figure 5). Whilst the rounded front end and greater glazed areas proposed within the original FKA concept were observed to improve direct vision performance when compared to traditional cab designs, changes to the instrument panel design, cab height and driver seating position were all found to further influence direct vision performance (Summerskill *et al.*, 2014).

Figure 5: Second design iteration of the FKA enhanced TFED concept with removal of the dash, a lowered driver position and additional glazed areas (Summerskill *et al.*, 2014).

It is important to note that the real-world usage of HGVs can differ widely between trucks designed for construction, distribution and long haulage transport. The size and type of vehicle also determines how challenging it could be to technically achieve a certain level of direct vision performance. This is particularly important when considering aspects such as engine packaging, which could result in different engineering and cost implications for different vehicle types. Different direct vision performance requirements could therefore be applied based on vehicle sizes and/or application related classifications, which better reflect the different involvement rates in relevant collisions.

This key point was discussed by stakeholders in Seidl *et al.* (2017), concluding that three key HGV classes (within the N2/N3 categories) could be identified based on application: urban delivery, large distribution and construction vehicles. Several differentiating criteria for these classifications were discussed including gross vehicle weights, axle counts and lengths. Clearly, this categorisation approach could also be extended to include a specific category for HGVs with enhanced TFEDs. Comparing direct vision performance against a best-in-class vehicle for each HGV class, instead of a single uniform approach, could therefore be used to benchmark performance against feasible cab designs that are highly suited to their applications (see the low entry cab designs in Annex 3.11). Best-in-class benchmark performance requirements for HGVs with enhanced TFEDs could therefore be set at a more stringent level to maximise the potential benefits that could be experienced by improving direct vision performance.

3.1.3 Possible overlaps in benefits and technology

The design of HGV cabs is a complex compromise between a range of competing factors, including the aerodynamics, manoeuvrability, mass distribution and packaging of a HGV, in addition to the safety measures reviewed by this project. When considering regulating the direct vision performance of enhanced TFEDs, it is clear that such requirements could encourage greater glazed areas, in addition to changes in the driver seating position and cab heights. Such dependencies in cab design could therefore prove either beneficial or detrimental to the overall cost-effectiveness of implementing direct vision requirements.

The effect of regulating the direct vision performance of enhanced TFEDs may therefore influence a range of factors, including those that are both considered within the scope of this particular project and those considered to be beyond the scope of this project. When considering the five safety measures reviewed by this project, regulating the direct vision performance of an enhanced TFED is likely to influence the costs and target populations of all safety measures. The majority of costs for reconstructing the front end of the truck may be shared with either the VRU impact protection [VIP] or front underrun protection [FUP] safety measures, whilst the target populations for the remaining safety measures will all be affected by the proportion of casualties that are prevented through improving direct vision performances. Finally, the greater glazed areas, lower cab heights and more forward driver seating positions that may be encouraged by such regulation, could also impact the effectiveness of the VIP and FUP safety measures by reducing the levels of protection afforded to HGV occupants.

When considering the influence of competing factors outside of the five safety measures investigated by this project, it is clear that many of the measures that were proposed by the General Safety Regulation review could also influence the target populations affected by direct vision performance requirements (Seidl *et al.*, 2017). This could include driver assist or active safety devices including: autonomous emergency braking for pedestrians and cyclists [AEBS-PC], lane keep assist [LKA], intelligent speed assist [ISA] and driver drowsiness and distraction recognition [DDR] devices. The potential effects of regulating direct visibility performance on factors such as the aerodynamic and the manoeuvrability performances of enhanced TFEDs should also potentially be considered.

To address this issue within the scope of this project, it is important to ensure that, when adapting any future regulation for enhanced TFEDs, the regulatory requirements consider the potential effects that regulating direct vision performance may have on cab design. This is especially important when considering VRU and cab occupant protection.

3.2 Potential Effects of Regulation

3.2.1 Target population

The annual target populations estimated for both fatally and seriously injured casualties relevant to the direct vision safety measure are shown below in Table 2. These target populations were calculated for pedestrians and cyclists, as these are the two populations primarily affected by improvements in HGV direct vision performance. The selection of appropriate target population ranges were performed to include all HGV collisions that involved VRUs during moving off, turning to nearside and turning to offside manoeuvres. Data from Robinson *et al.* (2016) was used to estimate the proportion of fatal collisions for both pedestrians and cyclists, whilst both Summerskill *et al.* (2014) and Schreck and Seiniger (2014) were used to estimate the ranges for serious injuries (Annex 1.3.3).

Table 2: Estimated annual target populations for the direct vision [DIR] safety measure and comparing both the differentiated and uniform approaches

	Uniform (*n*)			Differentiated (*n*)		
	Fatals	**Serious**	**KSI**	**Fatals**	**Serious**	**KSI**
Pedestrians	157	159-431	316-588	47	48-129	95-176
Cyclists	154	143-452	297-606	46	43-136	89-182
Total	311	302-883	613-1194	93	91-265	184-358

3.2.2 Estimates of effectiveness

The overall effectiveness values estimated for fatally and seriously injured casualties that were relevant to the direct vision safety measure are shown below in Table 3. For the purposes of estimating the overall effectiveness of the direct vision safety measure, the current best-in-class performance of HGV cab front ends was selected. As low-entry cabs (LECs) have been shown to have the highest level of direct vision performance (Robinson *et al.*, 2016), LECs were used to model the best-in-class performance currently available to enhanced TFEDs. The conclusions from a simulation study by Arup and the University of Leeds ITS group were then used to provide values for the differences in performance between the best-in-class LEC and a traditional HGV cab (Milner and Western-Williams, 2016). These values estimated the proportion of pedestrian and cyclist collisions that could be avoided by improving the direct vision performance of HGV cabs to current best-in-class levels (Annex 1.4.2). It must be noted that, as direct vision performance may be even further improved through regulating better direct vision for enhanced TFEDs, these values are considered a conservative estimate of effectiveness.

Table 3: Estimated overall effectiveness of the best-in-class technology for the direct vision [DIR] safety measure

	Fatals (%)	Serious (%)
Pedestrians	77-88	77-88
Cyclists	0-20	0-20

3.2.3 Cost implications

The costs of requiring best-in-class direct vision performance as part of the type-approval process for a HGV with an enhanced TFED can be divided into two categories based on:

1. Differences in development, manufacturing and approval costs due to the addition of the regulated feature
2. Differences in operational, environmental and infrastructure costs due to changes in the vehicle mass or payload

No objective data was found to consider the differences in development, manufacturing and approval costs due to the regulation of the direct vision performance of HGV cabs. Although the Arup cost-benefit study can be used to calculate costs of €3,500-10,000 per vehicle (when assuming adoption by the entire EU HGV fleet), this value only represents the costs associated with the development of a completely new high-visibility cab from its concept stage. When considering the direct vision safety measure covered by this review, however, the cost differential between an unregulated enhanced TFED (which would have been developed anyway for aerodynamic benefits) and an enhanced TFED that complies with the best-in-class direct vision performance requirements is clearly the most relevant costs to use. Unfortunately, no such information is currently publically available.

To provide an estimate of this additional cost, however, proxy values were used instead. The logic behind the selection of these proxy values was based on including the largest estimated costs per vehicle from the VIP and FUP safety measures. This was because it was expected that these values would represent the worst case costs based upon similar requirements for these particular safety measures. The greatest estimated cost range per vehicle was provided by the VIP safety measure, where costs of €400-600 per vehicle were estimated for a Safety Bar feature (Feist and Faßbender, 2008) (Table 4). This was multiplied by the total number of both HGVs and articulated trucks in the fleet to provide the total cost to industry when considering the differentiated and uniform approaches. Cost differentials resulting from operational, environmental or infrastructure costs were considered negligible due to no expected differences in vehicle mass/payload.

Table 4: Estimated costs per vehicle and total fleet costs of the best-in-class technology for the direct vision [DIR] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Costs (€/vehicle)	400-600	400-600
Total Fleet Costs (€Bn)	2.58-3.87	1.48-2.22

3.2.4 Cost effectiveness summary

Table 5 below summarises the estimated annual casualty reduction benefits that would be expected by regulating the direct vision performance of enhanced TFEDs to the best-in-class level. These values are then monetised to provide an estimate of the monetary benefits of the casualty reductions to the EU.

Table 5: Estimated annual casualty reduction benefits of the best-in-class technology for the direct vision [DIR] safety measure and comparing both the differentiated and uniform approaches

	Uniform			Differentiated		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Casualty Reduction (*n*)						
Pedestrians	121-138	123-379	244-517	36-41	37-114	73-155
Cyclists	0-31	0-90	0-121	0-9	0-27	0-36
Total	121-169	123-469	244-638	36-50	37-141	73-191
Monetised Benefits (€M)						
Pedestrians	189-216	28-88	218-304	57-65	9-26	65-91
Cyclists	0-48	0-21	0-69	0-14	0-6	0-21
Total	189-264	28-109	218-373	57-79	9-33	65-112

Finally, Table 6 provides estimates for the break-even costs and benefit-cost ratios over a 10-year time period according to the differentiated and uniform approaches.

Table 6: Estimated 10-year break-even costs and benefit-cost ratio per vehicle of the best-in-class technology for the direct vision [DIR] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Break-Even Costs (€/vehicle)	338-579	176-302
Benefit-Cost Ratio	*0.56-1.45*	*0.29-0.76*

3.2.5 Assessment of evidence

The level of evidence currently investigating the potential benefits of regulating the direct vision performance of HGVs with enhanced TFEDs is relatively low. Although a number of studies have assessed the effectiveness of direct vision, these have all compared direct vision performances between traditional HGV cab designs and LECs. It therefore remains unknown as to how effective enhanced TFEDs actually may be in reducing casualties.

Of the studies that evaluated direct vision performance effectiveness, only one provided empirical evidence that allowed the extrapolation of improved direct vision performance levels to the rates of VRU collisions avoided (Milner and Western-Williams, 2016). Whilst the majority of studies performed either case-by-case accident analyses or computational evaluations of driver fields of view for direct vision, Milner and Western-Williams (2016) investigated the proportion of pedestrian and cyclist collisions during a simulation study. Although this study was the highest level of evidence available to this review, and formed a critical aspect of the evidence base underpinning the effectiveness of the direct vision safety measure, there were a number of particular weaknesses associated with using this information (see Annex 1.4.2). More relevant research is therefore required to provide evidence that specifically answers this particular research question.

When considering the estimation of the target populations, only three studies provided a high enough level of evidence that characterised collisions between HGVs and VRUs by manoeuvre (Robinson *et al.*, 2016;Summerskill *et al.*, 2014;Schreck and Seiniger, 2014). Another two studies that provided similar evidence were eventually excluded based on the results not being generalizable enough to provide information regarding the overall European collision landscape, as they were based on a small selection of collisions in cities such as London (Knowles *et al.*, 2012;Talbot *et al.*, 2014).

Values for pedestrian and cyclist fatalities were extracted from Robinson *et al.* (2016). This was, however, the only study providing figures on fatal VRU collisions, so no ranges for the collisions could be extracted. Summerskill *et al.* (2014), on the other hand, failed to separate results between pedestrians and cyclists (providing values for all VRUs only) and injury severity levels (presenting values for all injuries only). Schreck and Seiniger (2014), however, provide the only collision analysis from data outside of Great Britain. The use of these values to estimate target populations, however, uses the best available evidence. Further collision analyses to refine these values are therefore recommended.

Finally, the evidence related to costs is also limited. No equivalent structures are on the market, nor have any working prototypes been developed. Cost estimates have therefore been approximated based on the costs associated with other safety measures. A specific stakeholder consultation with industry could therefore be appropriate for agreeing on the extra costs associated with requiring best-in-class direct vision performance.

Future publications that may better support the above estimations with a higher level of evidence are expected soon. A report from ACEA is expected to provide estimations of target populations and provide potential casualty benefit figures that are highly relevant to the direct vision safety measure. This will be based on data from national and in-depth collision databases and use a case-by-case analysis to provide effectiveness values. TfL have also recently commissioned two projects that aim to assess both the direct vision performance levels of a large number of HGV cabs currently available on the market and evaluate the impact of removing low-visibility HGVs from the roads of GB from both the economic and casualty benefit points of view.

3.3 Regulatory Considerations

When considering regulating the direct vision performance of enhanced TFEDs it is clear that any requirements should be underpinned via the adaptation of the HGV Direct Vision Standard (DVS). Whilst much of the DVS should remain unchanged, several compatibility issues between the DVS and HGVs with enhanced TFEDs have been identified. The main compatibility issue identified as part of this review lies in the definition of the assessment zones around the HGV cab. As the current DVS bases its requirements on the assumption that the HGV cab is a traditional, cuboid-shaped, cab-over-engine design, it specifies the assessment zones to be rectangular in shape and located at a distance of 0.3 m from the most frontal and lateral aspects of the cab (Figure 6) (Robinson *et al.*, 2016).

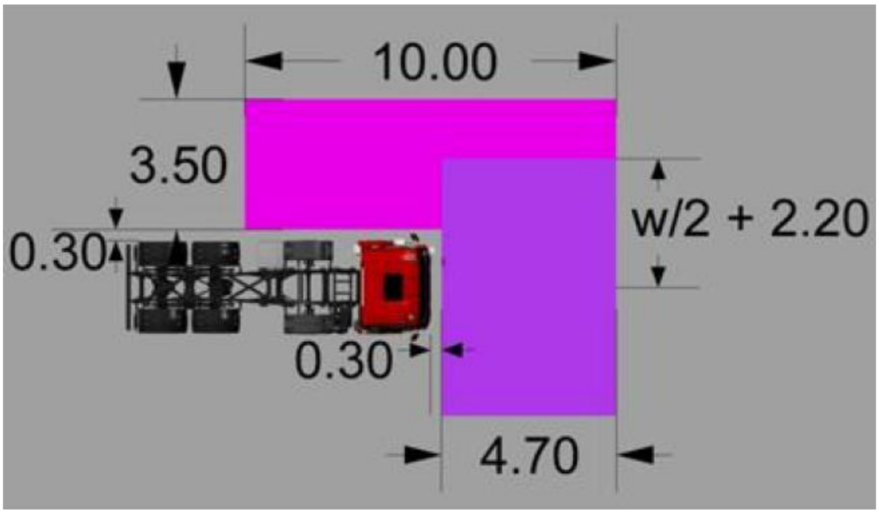


Figure 6: Specification for HGV Direct Vision Standard assessment zones for right-hand drive vehicles (Robinson *et al.*, 2016)

Clearly the specifications for these assessment zones are not appropriate for regulating HGVs with an enhanced TFED, as such designs would be expected to incorporate curved front ends. It may be more appropriate, therefore, to regulate direct vision performance levels of HGVs with enhanced TFEDs using assessment zones that follow the profile of the truck front end. Such an approach would only need to define the inner boundary of the assessment zone, as the accident scenarios that were used to define the outer boundary of the zones are still relevant, whilst it is likely that VRUs will still walk or cycle around the HGV by following its outermost profile. With this in mind it is recommended that the DVS is updated to ensure that the inner boundaries of the DVS assessment zones follow the outermost profile of the HGV and is offset by 0.3 m.

When considering the minimum requirements for a rated direct vision performance level, it would be beneficial to align this with the five star criteria proposed by the DVS, which corresponds to the direct vision performance rating scores currently achieved by LECs. This will therefore promote a level of direct vision performance that surpasses the three star levels currently achieved by articulated vehicles (Robinson *et al.*, 2016).

It is also important to ensure that, should HGVs with enhanced TFEDs enter production, any changes in either human behaviours or the collision landscape related to this change in design are captured in future updates of the DVS. It is entirely plausible that, in such a future, there may be a greater prevalence of offside turning collisions with both VRUs and cars, potentially due to the use of centralised driver seating locations, or VRUs may begin the process of crossing in front of the HGV from behind the driver seating position. These changes should, however, be reflected in future amendments of the DVS.

Finally, the effect of regulating direct vision performance on the structural integrity of the HGV cab should be controlled by ensuring that HGV designs that incorporate enhanced TFEDs still comply with Regulation 29. There is a risk that, by regulating the direct vision performance of HGVs with enhanced TFEDs, the cab glazed area is likely to increase and A-pillars reduce in size. Ensuring that Regulation 29 is still complied with by these new HGV designs would ensure there is no adverse reduction in HGV occupant safety with the introduction of direct vision requirements.

4 Indirect Vision (Mirrors, Cameras & Detection Systems)

4.1 Technical Considerations

4.1.1 Background on safety measure

Indirect Vision [IDV]

The indirect vision safety measure considered within this project concerns the field of vision available for indirectly observing and detecting the presence of "at risk" VRUs in close proximity to the HGV via assistive devices. These are limited to passive camera systems [CAM] and sensor-based detection systems [DET]. For clarity, sensor-based detection systems are limited to ultrasonic driver warning systems.

HGV blind spots have long been recognised as a significant contributory factor for serious collisions with VRUs such as pedestrians and cyclists (Smith, 2008;Cook *et al.*, 2010). Up to six mirrors, along with other field of view aids, are already required by Regulation 46 to improve the driver's view of blind spots (UNECE, 2016). These devices offer assistance to the driver by providing indirect visibility of these blind spots to identify any "at risk" VRUs that may be in close proximity to the HGV to prevent the occurrence of collisions.

Indirect vision, in the context of this project, refers to the indirect field of vision around the vehicle available to the driver through the aid of assistive devices such as mirrors or cameras or available to a sensor array through sensor-based detection systems. Because of this definition, the field of vision provided by such devices does not necessarily have to be provided in image form and can instead take the form of an audio-visual warning such as an alarm or flashing light.

UNECE Regulation 46 (R46) defines the current requirements for devices used for indirect vision purposes; with these devices including mirrors and Camera Monitoring Systems (CMS) only (see Annex 2.5). Mirrors are defined as a device intended to give a clear view to the rear, side or front of the vehicle, within the fields of vision, via a reflective surface. A CMS will consist of camera and monitor devices. Cameras are defined as a device that renders an image of the outside world and converts this image into a video signal. This signal is then converted into images which are displayed to the driver through a monitor.

R46 permits a CMS to be used instead of a mirror as long as the field of view is the same as, or larger than, the mirror it is replacing and the CMS meets the minimum technical requirements, such as magnification, resolution and colour range, specified within R46. There are no set requirements defining the minimum number of CMSs required to replace mirrors, although the number of monitors used to display images must not exceed the number of mirrors the CMS is intended to replace to prevent overload of the HGV driver.

R46 also describes the minimum areas that surround a HGV which must be visible to the driver through the assistance of indirect vision devices. This minimum area is divided into seven zones, four of which are mandatory for HGVs >7.5 tonnes (N2/N3 vehicles) (Table 7). The locations for these mandatory zones are also illustrated in Figure 7 overleaf.

Table 7: Indirect vision requirement zones for HGVs >7.5 tonnes (UNECE, 2016)

Zone	Mirror type	Status	# Mirrors
Class I	Interior rear-view mirror	Optional	1
Class II	Main exterior rear-view mirror	Mandatory	2
Class III	Main exterior rear-view mirror	N/A	N/A
Class IV	Wide-angle exterior mirror	Mandatory	2
Class V	Close-proximity exterior mirror	Mandatory *	1 (2)*
Class VI	Front mirror	Mandatory	1
Class VII	Main rear-view mirror	N/A	N/A

* Mandatory on passenger side, optional on driver side

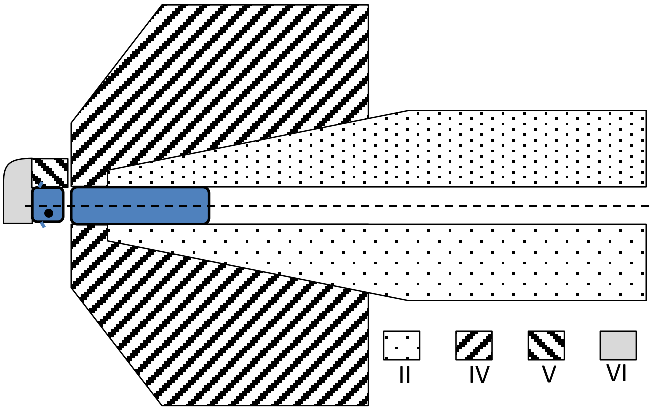


Figure 7: Mandatory HGV mirror classifications and illustration of regulated minimum visible areas for left-hand drive vehicles (adapted from R46 (UNECE, 2016), not to scale)

Rather than providing a visual image to the driver of the area surrounding the vehicle, sensor-based detection systems provide a warning to the driver in the form of audible, visual or haptic feedback (vibrating of the steering wheel). Whilst sensor-based detection devices are not currently regulated, it is clear that the zones defined in R46 for regulating the indirect vision field of view are just as applicable to these systems.

The field of view for such a detection system is principally dependent upon the detection angle and range of the system (with these determined by the technology used by the system) and so can range significantly between the different systems employed by HGVs. This variance is further compounded by a range of detection algorithms used by each system, which can also result in a large variation in detection rates between systems. It must be noted that, although detection systems can also provide an active response to a hazard, by either applying the brakes or adjusting the steering, this report only examines passive systems that provide a warning about VRUs or vehicles in proximity to the HGV.

Whilst each of these indirect vision safety measures provides a solution to the issue of enhancing the indirect field of view of the HGV driver, they all also have a number of disadvantages (Annex 1.4.3). Mirrors can be incorrectly positioned and drivers may not always monitor the correct mirror at the right time given the total number of mirrors (Dodd, 2009). They also render images at much smaller than life size, are often located in unnatural positions to look at (e.g. top corner of windscreen) and sometimes purposely distort the image to ensure a greater field of view can be monitored. Although camera or sensor-based detection systems are correctly positioned to view specific blind spots, the driver is still required to monitor a screen or recognise and react to a warning signal. In addition, camera monitoring systems are inherently limited during certain environmental conditions including adapting to extreme variations in light (driving at night and images "burnt-out" by direct sunlight) and the obscuration of images by spray or obstructions.

The review of this safety measure will therefore focus on solutions that provide levels of performance that exceed those provided by standard, R46 compliant, external mirrors. Specifically, this review will seek to evaluate the additional benefits and costs associated with camera monitoring systems and sensor-based detection systems when compared to these baseline values.

4.1.2 Opportunities for enhanced TFEDs

Current industry practice around the implementation of high-performance indirect vision assistance devices focuses around both integrated and aftermarket proprietary solutions (Annex 3.13). Camera Monitoring Systems (CMSs) may range in value and technological complexity, with systems ranging from single, low-cost, tractor mounted camera/monitor systems, to more expensive tractor and trailer mounted CMSs that provide 360° visibility around the HGV (Annex 3.13). Although CMSs are typically aftermarket solutions, a number of manufacturers have begun to offer both semi and fully integrated camera systems with new models (Volvo Trucks, 2014). For the purpose of this review, the cost-effectiveness of two CMS approaches will be evaluated; a 360° CMS providing visibility of Class II, V and VI zones and a blind-spot CMS providing visibility of Class V and VI zones.

In a similar sense to CMSs, there are also several integrated and aftermarket sensor-based detection systems currently available on the market (Annex 3.13). These systems range in value and technological complexity, with this primarily based on the technology underpinning the sensor system. Such systems can use ultrasonic sensors, in addition to cameras, to detect VRUs and vehicles in close proximity to the HGV. These technologies are also coupled with a number of approaches for warning the driver about "at risk" VRUs including audible, visual or haptic feedback. Again, while aftermarket solutions are widely available, integrated sensor-based detection systems are becoming much more prevalent (Daimler, n.d.). For the purpose of this review, the cost-effectiveness of two detection system approaches will be evaluated; a 360° system that detects VRUs in Class II, V and VI zones and a blind-spot system that detects VRUs in Class V and VI zones.

When considering current design proposals for HGVs with enhanced TFEDs, it is clear that the appropriate use of indirect vision devices to supplement or replace standard external mirrors may become central to ensuring the HGV aerodynamics are optimised (Annex 3). Aerodynamic issues already associated with external mirror designs could be exacerbated by HGVs with enhanced TFEDs that adopt curved front ends, increased glazed areas or driver seating positions that are located centrally or further forward within the cab. These design choices would require external mirrors that either provide greater reflective areas, or extend further away from the cab, to provide a field of view that is unobscured by the curved profile of the enhanced TFED. These mirrors also require mounting in front of the driver to external structures that may have been redesigned to improve direct vision. This presents a challenge from both the aerodynamic and regulatory perspectives, as larger external mirrors may reduce aerodynamic performance and R46 prohibits mirrors mounted below a height of 2 m from extending more than 250 mm from the cab edge.

The use of low-profile CMS devices to replace external mirrors may provide aerodynamic benefits whilst also ensuring compliance with the R46 requirements for the indirect vision field of view (Welfers *et al.*, 2011). This approach has been implemented by a number of enhanced TFED concepts (Annex 3), whilst also offering the opportunity for integration with camera-based detection systems and future blind-spot assistive devices. Finally the extra space presented by the curved front end designs currently adopted by enhanced TFEDs provides an opportunity to integrate sensor-based detection systems in the HGV front end. These can include both short-range ultrasonic sensors located around the front and sides of the HGV and longer range LIDAR/RADAR sensors at the front of the HGV. As the performance levels of sensor-based detection systems are not currently regulated, new requirements would therefore need developing for all HGVs before implementation.

4.1.3 Possible overlaps in benefits and technology

The effect of regulating the indirect vision performance of enhanced TFEDs may influence a range of factors, including both those considered in the scope of this particular project and those considered out of scope. When considering the five safety measures reviewed in this project, regulating the indirect vision performance of enhanced TFEDs to improve performance is likely to influence the target populations of all safety measures aside from the direct vision [DIR] safety measure. The target populations for both approaches to improving indirect vision performance are also dependent on each other, with both the camera and detection systems capable of preventing potential collisions 360° around the HGV. When considering clustering costs, however, it is clear this would come primarily by combining cameras with detection systems to reduce sensor costs.

When considering the influence of competing factors outside of the five safety measures investigated by this project, it is clear that many of the measures that were proposed by the General Safety Regulation review could also influence the target populations affected by indirect vision performance requirements (Seidl *et al.*, 2017). This could include driver assist or active safety devices including: autonomous emergency braking for pedestrians and cyclists [AEBS-PC], lane keep assist [LKA], intelligent speed assist [ISA] and driver drowsiness and distraction recognition [DDR] devices.

To address this issue within the scope of this project, it is important to ensure that, when adapting any future regulation for enhanced TFEDs, the regulatory requirements consider the potential effects of likely cab designs on regulating indirect vision performance.

4.2 Potential Effects of Regulation

4.2.1 Target population

The annual target populations estimated for both fatally and seriously injured casualties relevant to the indirect vision safety measure are summarised below in Table 8. These have been calculated for pedestrians and cyclists, as these are the populations primarily affected by improvements in the indirect vision performance of HGVs. As two approaches have been proposed for each indirect vision device, two target populations were defined for each device. Target populations for the 360° approach included all HGV collisions that involved VRUs during moving off, turning to nearside, turning to offside and sideswipe manoeuvres, whilst target populations for the blind-spot approach included all collisions involving VRUs during moving off and turning to nearside manoeuvres only. These target populations were considered equivalent for each approach, regardless of the device. Data from Robinson *et al.* (2016) was used to estimate the proportion of fatal collisions for both pedestrians and cyclists, whilst Summerskill *et al.* (2014) and Schreck and Seiniger (2014) were used to estimate the ranges for serious injuries (Annex 1.3.3).

Table 8: Estimated annual target populations for the indirect vision [IDV] safety measure (including 360° and blind-spot cameras [CAM] and detection systems [DET]) and comparing both the differentiated and uniform approaches

	Uniform (*n*)			Differentiated (*n*)		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Camera/Detection Systems (360°)						
Pedestrians	174-192	187-487	361-679	52-58	56-146	108-204
Cyclists	163-171	168-503	331-674	49-51	50-151	99-202
Total	337-363	355-990	692-1353	101-109	106-297	207-406
Camera/Detection Systems (Blind-Spot)						
Pedestrians	141	159-319	300-460	42	48-96	90-138
Cyclists	137	143-351	280-488	41	43-105	84-146
Total	278	302-670	580-948	83	91-201	174-284

4.2.2 Estimates of effectiveness

The overall effectiveness values estimated for fatally and seriously injured casualties that were relevant to the indirect vision safety measure are shown overleaf in Table 9. For the purposes of estimating the overall effectiveness of the indirect vision safety measure, a range of effectiveness values were selected based on the indirect vision device, approach and target population. To estimate overall effectiveness, the effectiveness of each device in reducing blind spots was combined with driver reaction and sensor activation factors (if appropriate) to account for the diagnostic accuracy of the device and driver behaviour.

The overall effectiveness for 360° camera monitoring systems (CMSs) was estimated by assuming that a single CMS could replace multiple mirrors (Classes II, V and VI) and that multiple CMS images could be stitched together and displayed as one continuous image (Annex 3.13). The 360° CMS was therefore assumed to be best-in-class, thus eliminating 100% of blind spots around the entire HGV. A driver reaction factor of 17-33% was then applied based on the proportion of time that a driver would check the monitor during a manoeuvre. Given it is currently mandatory to have six mirrors and the 360° CMS would require 3 mirrors/monitors, it was assumed that the lower boundary of the effectiveness range could be determined by the differences in the proportions of time that a HGV driver would perform monitor check (1/6th vs. 1/3rd of their time). The upper boundary for this range was then estimated based on the proportion of time that a HGV driver would take to check the monitor when using the 360° approach during a manoeuvre (1/3rd of their time). These factors were calculated by assuming that all mirror/monitor checks take an equal amount of time and that drivers always check their mirrors/monitors in situations where VRUs are "at risk".

The overall effectiveness for blind-spot CMSs was estimated in a similar manner. It was assumed that the blind-spot CMS would replace Class V and VI mirrors and that multiple camera images could also be stitched together (Annex 3.13). The blind-spot CMS was also assumed to be best-in-class, thus eliminating 100% of blind spots in the Class V and VI zones. As the blind-spot CMS would reduce the number of mirrors/monitors to a total of five systems, this corresponded to the HGV driver spending 1/5th of their time looking at the CMS monitor during manoeuvres. Overall effectiveness was therefore estimated to be between 3-20%.

The 360° detection system was assumed to position sensors around the entire perimeter of the HGV, whilst the blind-spot detection system was assumed to locate sensors around the front and nearside of the HGV cab. Both systems were assumed to be best-in-class, thus eliminating 100% of blind spots in their respective areas. A sensor activation factor (the proportion of time that the sensors will correctly identify and warn of pedestrians or cyclists) was applied based on pedestrian and cyclist AEBS detection rates from Rosen (2013). These ranged between 42% and 58%, based upon both target population and injury severity, and were also adopted by Seidl *et al.* (2017). The driver reaction factor was based upon a human-machine interface factor of 80%, as recommended by Kuehn *et al.* (2009), which takes into consideration the response rate of the driver to positive detections of “at risk” VRUs. The overall effectiveness for these sensor-based detection systems was therefore estimated to range between 26-46%.

Table 9: Estimated overall effectiveness for the indirect vision [IDV] safety measure (including 360° and blind-spot cameras [CAM] and detection systems [DET])

	Camera Systems (360°)		Camera Systems (Blind-Spot)		Detection Systems (Both)	
	Fatals (%)	Serious (%)	Fatals (%)	Serious (%)	Fatals (%)	Serious (%)
Pedestrians	17-33	17-33	3-20	3-20	38-40	33-34
Cyclists	17-33	17-33	3-20	3-20	42-46	26-27

4.2.3 Cost implications

The costs of requiring best-in-class indirect vision performance as part of a type-approval process for a HGV with an enhanced TFED is primarily dependent upon the costs of the technology used for the indirect vision device. Estimated costs for each best-in-class technology solution were primarily based on an approach adopted by Seidl *et al.* (2017). The costs of aftermarket solutions were first researched (Annex 1.5.3), before reducing these costs by a fixed factor to one third the value to estimate the OEM costs for integrating the best-in-class solution into the HGV design.

When considering both the 360° and blind-spot camera monitoring systems, the lower cost boundaries were calculated based on the lowest available aftermarket costs for each CMS. These costs were calculated based on the costs provided within Commercial Motors (2017), where the lowest cost of the first camera and monitoring system was found to be €283 and with every camera added after that costing an extra €170. The key differences between the 360° and blind-spot CMSs was that the 360° CMS was assumed to require four cameras, whilst the blind-spot CMS was assumed to require only two. The upper cost boundary for the blind-spot CMS was also based on costs provided by Commercial Motors (2017), whilst the upper camera and monitoring system cost boundary was found to be €396, with every camera added after that costing an extra €170. The upper cost boundary for a 360° CMS was, however, found to be €1695 based on costs specific to an aftermarket solution from Brigade (2017).

When considering the 360° and blind-spot detection systems, the lower and upper cost boundaries were calculated based on the costs for aftermarket ultrasonic sensor systems. These costs were estimated based on costs provided by Commercial Motors (2017) and HGV Direct Parts (2017), where the lowest cost of an ultrasonic senor system was found to be €147 and the highest cost was €215. The key differences between the 360° and blind-spot detection systems was that the 360° system was assumed to require eight sensors, whilst the blind-spot system was assumed to require only three sensors.

These costs were then multiplied by the total number of both HGVs and articulated trucks in the fleet to provide the total cost to industry when considering both the differentiated and uniform approaches (Table 10).

Table 10: Estimated costs per vehicle and total fleet costs for the indirect vision [IDV] safety measure (including 360° and blind-spot cameras [CAM] and detection systems [DET]) and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Camera Systems (360°)		
Costs (€/vehicle)	264-565	264-565
Total Fleet Costs (€Bn)	1.70-3.64	0.98-2.09
Camera Systems (Blind-Spot)		
Costs (€/vehicle)	151-188	151-188
Total Fleet Costs (€Bn)	0.97-1.21	0.56-0.70
Detection Systems (360°)		
Costs (€/vehicle)	392-573	392-573
Total Fleet Costs (€Bn)	2.52-3.69	1.45-2.12
Detection Systems (Blind-Spot)		
Costs (€/vehicle)	147-215	147-215
Total Fleet Costs (€Bn)	0.95-1.38	0.54-0.79

4.2.4 Cost effectiveness summary

Table 11 below summarises the estimated annual casualty reduction benefits that would be expected by regulating the indirect vision performance of enhanced TFEDs to the best-in-class levels for 360° and blind-spot camera monitoring systems. These values are then monetised to provide an estimate of the monetary benefits to the EU.

Table 11: Estimated annual casualty reduction benefits for the indirect vision [IDV] safety measure (including 360° and blind-spot cameras [CAM] only) and comparing both the differentiated and uniform approaches

	Uniform			Differentiated		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Camera Systems (360°)						
Casualty Reduction (*n*)						
Pedestrians	29-63	31-161	60-224	9-19	9-48	18-67
Cyclists	27-57	28-166	55-223	8-17	8-50	16-67
Total	56-120	59-327	115-447	17-36	17-98	34-134
Monetised Benefits (€M)						
Pedestrians	45-99	7-37	53-136	14-30	2-11	16-41
Cyclists	42-89	6-38	49-127	13-27	2-12	15-38
Total	88-187	14-76	102-263	26-56	4-23	30-79
Camera Systems (Blind-Spot)						
Casualty Reduction (*n*)						
Pedestrians	5-28	5-64	10-92	1-8	2-19	3-27
Cyclists	5-27	5-70	10-97	1-8	1-21	2-29
Total	10-55	10-134	20-189	2-16	3-40	5-56
Monetised Benefits (€M)						
Pedestrians	7-44	1-15	9-59	2-13	0.3-4	3-18
Cyclists	7-43	1-16	8-59	2-13	0.3-5	2-18
Total	14-87	2-31	17-118	4-26	1-9	5-35

Table 12 overleaf summarises the estimated annual casualty reduction benefits that may be expected by regulating the indirect vision performance of enhanced TFEDs to the best-in-class levels for 360° and blind-spot detection systems. These values are then monetised to provide an estimate of the monetary benefits to the EU.

Table 12: Estimated annual casualty reduction benefits for the indirect vision [IDV] safety measure (including 360° and blind-spot detection systems [DET] only) and comparing both the differentiated and uniform approaches

	Uniform			Differentiated		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Detection Systems (360°)						
Casualty Reduction (*n*)						
Pedestrians	67-76	63-165	130-241	20-23	19-50	39-73
Cyclists	68-80	43-134	131-214	20-24	13-40	33-64
Total	135-156	126-299	261-455	40-47	32-90	72-137
Monetised Benefits (€M)						
Pedestrians	104-119	14-38	119-158	31-36	4-11	36-47
Cyclists	106-124	10-31	116-156	32-37	3-9	35-47
Total	210-244	24-69	235-313	63-73	7-21	70-94
Detection Systems (Blind-Spot)						
Casualty Reduction (*n*)						
Pedestrians	54-56	53-108	107-164	16-17	16-32	32-49
Cyclists	57-63	37-94	94-157	17-19	11-28	28-47
Total	111-119	90-202	201-321	33-36	27-60	60-96
Monetised Benefits (€M)						
Pedestrians	85-88	12-25	97-57	25-26	4-8	29-34
Cyclists	89-99	9-22	97-121	27-30	3-7	29-36
Total	173-187	21-23	194-234	52-56	6-14	58-70

Finally, Table 13 provides estimates for the break-even costs and benefit-cost ratios over a 10-year time period according to the differentiated and uniform approaches.

Table 13: Estimated 10-year break-even costs and benefit-cost ratio per vehicle for the indirect vision [IDV] safety measure (including 360° and blind-spot cameras [CAM] and detection systems [DET]) and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Camera Systems (360°)		
Break-Even Costs (€/vehicle)	158-408	82-213
Benefit-Cost Ratio	*0.28-1.55*	*0.15-0.81*
Camera Systems (Blind-Spot)		
Break-Even Costs (€/vehicle)	26-183	14-96
Benefit-Cost Ratio	*0.14-1.22*	*0.07-0.63*
Detection Systems (360°)		
Break-Even Costs (€/vehicle)	364-486	190-254
Benefit-Cost Ratio	*0.64-1.24*	*0.33-0.65*
Detection Systems (Blind-Spot)		
Break-Even Costs (€/vehicle)	302-363	157-190
Benefit-Cost Ratio	**1.40-2.47**	*0.73-1.29*

4.2.5 Assessment of evidence

The level of evidence underpinning the potential benefits of regulating the indirect vision performance of HGVs with enhanced TFEDs is relatively low. Although a number of studies have assessed the effectiveness of indirect vision devices, these have all been compared using traditional HGV cab designs. It therefore currently remains unknown as to how effective enhanced TFEDs that use high-performance indirect vision devices could actually be in reducing casualties.

Of the studies evaluating the effectiveness of indirect vision devices, none were found to provide any empirical evidence that allowed for the direct extrapolation of improvements in indirect vision performance to the rates of VRU collisions avoided. The calculations for overall effectiveness were therefore based on a combination of indirect measures rather than casualty reduction benefits for each indirect vision device. The effectiveness of best-in-class CMS and detection systems were estimated based on the assumption that these devices remove all blind spots for two different approaches; a 360° field of vision and a field of vision forward and to the nearside of a cab. To estimate the duration that drivers may be looking at any single mirror or monitor, Taoka (1990) estimated that all mirrors are looked at for the same amount of time. The driver reaction factors for the detection systems were based on an estimation made by Kuehn *et al.*, (2009), whilst the sensor activation factors were based on pedestrian and cyclist detection rates for AEBS systems fitted to cars (Rosen, 2013). Although the use of these approximations was necessary due to the absence of a relevant evidence base, there still remained several weaknesses with the quality of evidence provided within these less relevant studies. More relevant research is therefore still required to provide an evidence base that specifically answers this particular research question.

When considering the estimation of the target populations, only three studies provided a high enough level of evidence that characterised collisions between HGVs and VRUs by manoeuvre (Robinson *et al.*, 2016;Summerskill *et al.*, 2014;Schreck and Seiniger, 2014). Another two studies that provided similar evidence were eventually excluded based on the results not being generalizable enough to provide information regarding the overall European collision landscape, as they were based on a small selection of fatal collisions in cities such as London (Knowles *et al.*, 2012;Talbot *et al.*, 2014).

Values for pedestrian and cyclist fatalities were extracted from Robinson *et al.* (2016). This was, however, the only study providing figures on fatal VRU collisions, so no ranges for the collisions could be extracted. Summerskill *et al.* (2014), on the other hand, failed to separate results between pedestrians and cyclists (providing values for all VRUs only) and injury severity levels (presenting values for all injuries only). Schreck and Seiniger (2014), however, provide the only collision analysis from data outside of Great Britain. The use of these values to estimate target populations, however, uses the best available evidence. Further collision analyses to refine these values are therefore recommended.

Finally, the evidence base related to costs has only partially been verified with industry. These costs were based on the approach adopted by Seidl *et al.* (2017), where a range of retail prices for aftermarket solutions were acquired and reviewed, before estimating the costs for OEM integration by reducing these costs by one-third. Whilst this project took a similar approach to that defined by Seidl *et al.* (2017), a specific stakeholder consultation with industry would be appropriate for verifying the extra costs associated with requiring integrated devices that provide best-in-class indirect vision performance.

Future publications that may better support the above estimations with a higher level of evidence are expected soon. A report from ACEA is expected to provide estimations of target populations and provide potential casualty benefit figures that are highly relevant to the indirect vision safety measure. This will be based on data from both national and in-depth collision databases and case-by-case analyses to provide effectiveness values. This will be further supported by the release of the Volvo Trucks Accident Research Team safety report which will provide target population data based on the analysis of a number of international, national and in-depth collision analysis databases.

4.3 Regulatory Considerations

When considering regulating the indirect vision performance of enhanced TFEDs it is clear that any requirements should be underpinned via the adaptation of Regulation 46. Whilst much of R46 should remain unchanged, several compatibility issues between R46 and HGVs with enhanced TFEDs have been identified. The main compatibility issue identified as part of this review lies in the definition of the assessment zones around the HGV cab. R46 bases its requirements on the assumption that the HGV cab is a traditional, cuboid-shaped, cab-over-engine design, specifying the assessment zones as bounded by vertical planes that are located based on dimensions taken from the outermost points of the HGV cab and the ocular position of the driver (UNECE, 2016). This is perhaps most important for both the Class V and VI field of view requirements which could create new blind spots around the front end of the HGV (Figure 8).

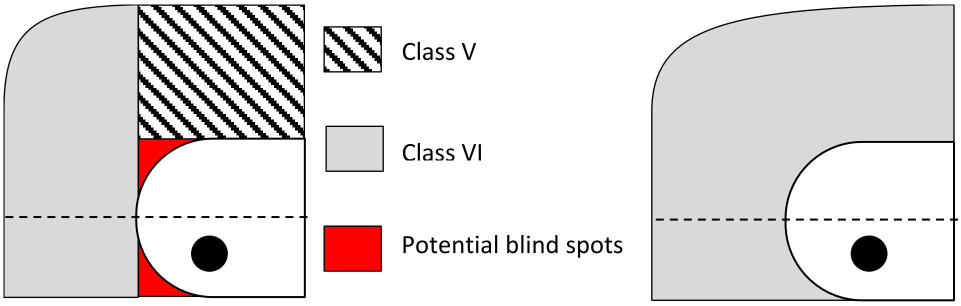


Figure 8: Potential blind spots created by a curved front end with current Regulation 46 indirect vision requirements (left) and potential solution (right) (not to scale)

Clearly the specifications for these assessment zones are not appropriate for regulating HGVs with an enhanced TFED, as such designs would be expected to incorporate curved front ends. It may therefore be more appropriate to regulate indirect vision performance in close proximity to the vehicle using a single assessment zone that follows the profile of the truck front end (Figure 8). Such an approach would only need to define the outer boundary of the assessment zone, as the inner boundary would be defined based on the outermost profile of the HGV. HGV manufacturers could be encouraged to implement a combination of devices to provide this field of view, but requirements should be placed on the maximum number of monitors/mirrors provided to the driver to avoid driver overload and the maximum permissible distortion of any images.

Furthermore, introducing the regulation of detection systems will require development of new requirements to ensure minimum performance levels. Although no such legislation currently exists for HGVs, there are ongoing activities that are developing requirements for addressing the regulation of turn assist systems for HGVs (UNECE, 2015c). Although this research investigates at the dynamic detection of cyclists located on the nearside of the HGV, the efforts of this research could be used to guide the adoption of requirements for detection systems that detect VRUs located in close proximity to the front end of the HGV (i.e. in the Class V and VI zones). Further research is currently being performed by TfL to develop testing and assessment protocols that focus on certification of HGV blind spot safety warning devices.

It is important to also note that the objectives of R46 and the HGV Direct Vision Standard (DVS) are also closely aligned. The Class V and Class VI assessment zones specified by R46 and the DVS assessment zones both aim to improve the capability of the driver to detect VRUs in close proximity to the HGV. Although these zones do not perfectly align, there is clearly scope to provide a harmonised approach for regulating the field of view of the driver in close proximity to the HGV. As drivers have been shown to react 0.7s slower when using indirect vision devices rather than direct vision (Milner and Western-Williams, 2016), it is also important to note that direct vision may be more beneficial to eliminating blind spots than indirect vision.

Finally, it is important to ensure that, if HGVs with enhanced TFEDs enter production, any changes in either human behaviours or the collision landscape related to this change in design are captured in future regulatory updates. It is entirely plausible that, in such a future, there may be a greater prevalence of offside turning collisions with both VRUs and cars, potentially due to the use of centralised driver seating locations, or VRUs may begin the process of crossing in front of the HGV from behind the driver seating position. These changes should, however, be reflected in future regulatory amendments.

5 Vulnerable Road User Impact Protection

5.1 Technical Considerations

5.1.1 Background on safety measure

VRU Impact Protection [VIP]

The VRU impact protection safety measure considered by this project concerns the structural components, excluding the front underrun protection (FUP) system, located at the front end of the HGV that optimises opponent compatibility and prevent run over events during frontal collisions involving VRUs.

Collisions between HGVs and VRUs consist of three phases: the primary impact between the front of the HGV and the VRU, the secondary impact between the VRU and the ground (or other surrounding roadside furniture or structures), and finally, the run-over phase. Depending on the precise circumstances of the collision, not all of these phases may be present. However, since current truck designs are optimised for load space within permitted dimensions, the front face is typically a vertical, flat surface. In collisions with VRUs, although distributing the loads evenly, the impacts can be highly injurious and the shape of the vehicle front tends to push the VRU over, thereby increasing the risk of a run-over phase occurring.

The safety solutions discussed in this section are those designed to improve the protection offered by the front of the HGV for an impact with a pedestrian or cyclist, referred to hereafter as vulnerable road users (VRUs). There are currently no pedestrian safety requirements for HGVs, since Regulation 127 is only applicable to M1 and N1 category vehicles (UNECE, 2015).

The main function of improved VRU protection is to reduce the peak acceleration experienced by the VRU during the primary impact. This protection is conferred by the structural deformation which controls acceleration of the vulnerable road user up to the limit of the structure. This leads to two important considerations relating to the phases of the impact to which protection can be provided and the limits of this protection.

An improved, VRU-friendly HGV front would have no effect on the secondary phase. However, the geometry of the truck front end has been shown to be important with respect to providing directional input away from the vehicle’s path, thereby reducing the risk of run-over. In terms of the limits of protection, a deformable structure provides a finite ‘ride-down’ before stiffer structures of the HGV are contacted.

The main technical solution is a ‘nosecone’ design that increases the length of deformable structure to offer more protection to VRUs in the primary impact (see Figure 9). The geometry of the nosecone aims to direct VRUs away from the vehicle’s path, thereby reducing the risk of being run over after the primary and secondary impacts.

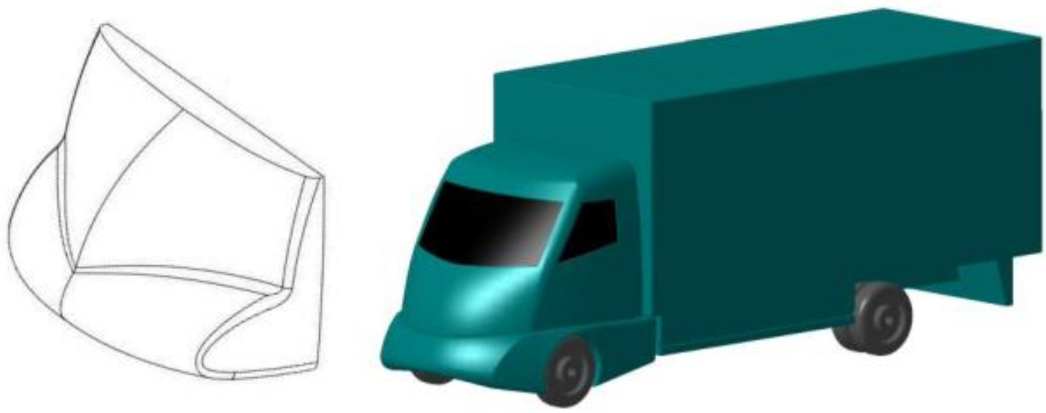


Figure 9: APROSYS optimised nosecone geometry (Feist and Faßbender, 2008)

Research by the APROSYS project showed that improved protection termed the 'safety bar' (essentially an energy absorbing frame that could be retro-fitted to the front of trucks) reduced the risk of head and lower extremity injuries by up to 90% at impact speeds of up to 40 km/h (Feist and Faßbender, 2008). This study also demonstrated that modified front profiles ('nosecones') were successful at reducing the risk of run over by deflecting the VRU from the vehicle's path and that the nosecone geometry could be complemented by improved primary impact protection because the additional length could be used for energy absorbing material.

5.1.2 Opportunities for enhanced TFEDs

Current truck designs are optimised for load-carrying capability within the permitted dimensions. This has resulted in a typical HGV having a vertical, flat front end with no pedestrian safety requirements to demand a different design. The effects of this are two-fold in terms of VRU collisions; low primary impact protection in the event of a collision and direct visibility blind spots, thereby contributing to the frequency of collisions.

A curved frontal geometry (a 'nosecone') However, research work such as that carried out for APROSYS on a 'nosecone' design (see Annex 3.5) shows benefits for VRU primary impact protection by utilising energy absorbing material and also for avoiding run-over by deflecting the VRU to the side and away from the path of the vehicle.

5.1.3 Possible overlaps in benefits and technology

The purpose of the improved VRU impact protection is to mitigate VRU injury and therefore other technologies with this objective would result in overlaps with respect to the target population of VRUs that could be influenced.

These areas include overlaps with technologies that might reduce the target population of VRUs (where the current target population estimates are based on accident statistics):

- Improved direct and indirect visibility
- Fitment of Pedestrian and cyclist AEB (for avoidance)

These two aspects are likely to be complementary to improved VRU impact protection with no design conflicts. For example, nosecone designs have been shown via modelling to be generally complementary to improved direct visibility, with nosecones up to 400mm or longer eliminating the blind spot for a 5th percentile female. Larger nosecones (1000mm plus) with a high vertical position were shown to obscure a child, but a child would still be detectable closer to the truck front compared to a standard truck (Robinson *et al.*, 2010).

In addition, overlaps in casualty benefit might be brought about by technologies that influence the effectiveness of the VRU impact protection:

- VRU airbag systems
- Fitment of Pedestrian and cyclist AEB (for mitigation) and bringing a proportion of the VRUs that could not be protected initially, to levels for which the improved VRU protection could confer benefit
- Front underrun protection where these structures may provide a degree of deformable structure

The first two of these aspects are also considered complementary to improved VRU protection. Changing the shape of the truck front with a nosecone design means that the mounting position for external airbags could be aligned with the wrap around distance and also the initial point of contact. AEB systems – providing the sensing is not impeded by a changed front profile – would be entirely complementary and could be linked to external airbag systems. Front underrun protection is likely to provide some complementary benefits, but optimisation in the additional length available could conflict with the optimum VRU protection.

5.2 Potential Effects of Regulation

5.2.1 Target population

The annual target populations estimated for both fatally and seriously injured casualties relevant to the VRU impact protection safety measure are shown below in Table 14. These have been calculated for pedestrians and cyclists, as these are the two populations primarily affected by improvements in the VRU impact protection performance of HGVs. The selection of an appropriate target population range was performed to include all collisions involving VRUs impacting the front end of the HGV. Robinson *et al.* (2016) and Robinson and Chislett (2010) were used to estimate the proportion of fatalities, whilst the studies by Summerskill *et al.* (2017) and Robinson and Chislett (2010) estimated the ranges for serious injuries (Annex 1.3.3). It is important to note that it was not possible to estimate the proportion of VRUs injured during primary or secondary impacts or during run-over impacts.

Table 14: Estimated annual target populations for the VRU impact protection [VIP] safety measure and comparing both the differentiated and uniform approaches

	Uniform (*n*)			Differentiated (*n*)		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Pedestrians	401-415	339-426	740-841	120-124	102-128	222-252
Cyclists	92-104	225-256	317-360	28-31	68-77	96-108
Total	493-519	564-682	1057-1201	148-155	170-205	318-360

5.2.2 Estimates of effectiveness

The overall effectiveness values estimated for fatally and seriously injured casualties that were relevant to the VRU impact protection safety measure are shown below in Table 15. For the purposes of estimating the overall effectiveness of the VIP safety measure, both the current best-in-class and mid-range performance levels were selected. These two effectiveness levels were selected to provide a comparison of costs and benefits for two key scenarios: the entire cab length extension being used for the VIP device and the cab length extension being used for a combination of VIP and FUP devices.

Table 15: Estimated overall effectiveness of the best-in-class and mid-range designs for the VRU impact protection [VIP] safety measure

	Best-in-Class TFED Extension (1.0 m)		Mid-Range TFED Extension (0.5 m)	
	Fatals (%)	Serious (%)	Fatals (%)	Serious (%)
Pedestrians	47-63	47-63	29-42	29-42
Cyclists	47-63	47-63	29-42	29-42

Two key studies were used for estimating the benefits of the current best-in-class and mid-range VIP performance levels. Robinson *et al.* (2010) estimated the proportion of GB fatalities that could be prevented by tapered front end designs that had been extended in length by a range of values between 200-1000 mm. The study found that, if all HGVs had a tapered TFED to deflect VRUs, between 29-47% of fatalities related to frontal impacts could be prevented. When considering designs providing best-in-class protection, a TFED extension of 1000 mm was found to be capable of preventing 47% of fatalities. When considering mid-range levels of protection, however, a TFED extension of 500 mm could potentially prevent only 29% of fatalities (Robinson *et al.*, 2010). Welfers *et al.* (2011) estimated the proportion of fatalities that could be prevented by a range of HGV TFEDs based on the FKA concept. The study found that, if all HGVs adopted a cab extension of 800 mm, between 42-63% of fatalities related to frontal impacts could be prevented.

Based on these values the overall effectiveness range for a best-in-class TFED extension was taken from the upper boundaries of the values from both Robinson *et al.* (2010) and Welfers *et al.* (2011). Subsequently, when considering the overall effectiveness range for mid-range TFED extensions, the effectiveness values were estimated based on the lower boundary values from these studies. These proportions were assumed to be transferrable to the serious injury category, as no research was found to categorise the effectiveness for this particular injury severity level.

5.2.3 Cost implications

The costs of compliance with VRU impact protection performance levels as part of a type-approval process for HGVs with enhanced TFEDs can be divided into two categories:

1. Differences in development, manufacturing and approval costs due to the addition of the regulated feature
2. Differences in operational, environmental and infrastructure costs due to changes in the vehicle mass or payload

Very little objective and accurate information is available on the likely costs associated with requiring VRU impact protection for a revised front-end design, when compared to revising the front end design without these requirements. The estimate below in Table 16 is derived from Feist and Faßbender (2008), which calculated the additional costs for the manufacture of the "Safety Bar" impact protection feature (Annex 3.5).

Table 16: Estimated costs per vehicle and total fleet costs of the best-in-class designs for the VRU impact protection [VIP] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Costs (€/vehicle)	400-600	400-600
Total Fleet Costs (€Bn)	2.58-3.87	1.48-2.22

These estimates, however, relate only to the costs in item 1 above. Feist and Faßbender (2008) estimated that the addition of the Safety Bar feature could conceivably add 20-70 kg to the mass of a truck. Robinson *et al.* (2010) modelled the journey cost generation effect of adding a mass of between 125-250 kg as a consequence of an enhanced TFED and showed that at the upper end of that range the costs outweighed the benefits. Accurately modelling journey cost generation effects is, however, extremely complex and sometimes controversial and so is not included here.

5.2.4 Cost effectiveness summary

Table 17 and Table 18 below summarise the estimated annual casualty reduction benefits that would be expected by regulating the VRU impact protection performance of HGVs with enhanced TFEDs to either the best-in-class or mid-range levels. These values are then monetised to provide estimates of the monetary benefits of the casualty reductions to the EU, with the mid-range TFED extensions sharing the benefits with the mid-range FUP safety measure.

Table 17: Estimated annual casualty reduction benefits of the best-in-class designs for the VRU impact protection [VIP] safety measure and comparing both the differentiated and uniform approaches

	Uniform			Differentiated		
	Fatals	**Serious**	**KSI**	**Fatals**	**Serious**	**KSI**
Best-in-Class TFED Extension (1.0 m)						
Casualty Reduction (*n*)						
Pedestrians	188-261	159-268	347-529	56-78	48-80	104-158
Cyclists	43-65	106-161	149-226	13-20	32-48	45-68
Total	231-326	265-429	496-755	69-98	80-128	149-226
Monetised Benefits (€M)						
Pedestrians	295-409	37-62	331-471	88-123	11-19	99-141
Cyclists	67-102	24-37	92-139	20-31	7-11	28-42
Total	362-511	61-99	423-610	109-153	18-30	127-183

Table 18: Estimated annual casualty reduction benefits of the mid-range designs for the VRU impact protection [VIP] safety measure and comparing both the differentiated and uniform approaches

	Uniform			Differentiated		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Mid-Range TFED Extension (0.5 m)						
Casualty Reduction (*n*)						
Pedestrians	116-174	98-179	214-353	35-52	30-54	65-106
Cyclists	27-44	65-108	92-152	8-13	20-32	28-45
Total	143-218	163-287	306-505	43-65	50-86	93-151
Monetised Benefits (€M)						
Pedestrians	182-272	23-41	205-314	55-81	7-12	61-94
Cyclists	42-68	15-25	57-93	12-20	5-7	17-28
Total	223-340	38-66	261-407	67-102	11-20	78-122

Finally, Table 19 provides estimates for the break-even costs and benefit-cost ratios over a 10-year time period according to the differentiated and uniform approaches, with the mid-range TFED extensions sharing both costs and benefits with the mid-range FUP safety measure.

Table 19: Estimated 10-year break-even costs and benefit-cost ratio per vehicle of the best-in-class and mid-range designs for the VRU impact protection [VIP] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Best-in-Class TFED Extension (1.0 m)		
Break-Even Costs (€/vehicle)	657-947	343-495
Benefit-Cost Ratio	**1.10-2.37**	*0.57-1.24*
Mid-Range TFED Extension (0.5 m)		
Break-Even Costs (€/vehicle)	406-631	212-330
Benefit-Cost Ratio	*0.68-1.58*	*0.35-0.82*

5.2.5 Assessment of evidence

The level of evidence on design changes to improve VRU protection is good although is limited to a relatively small number of studies. The scientific theory on extended 'nosecones' both in terms of the additional energy absorbing capability in impacts and the ability to redirect VRUs away from the striking vehicle's path is strong and is reinforced by the studies reviewed for this project. The studies also show that changes in front geometry also have benefits for direct visibility.

Only two studies were used to generate the estimates for effectiveness and these were both based on fatal casualties. For these casualties, the phase of the collision in which they were injured was unknown. The improvements considered affect the primary and run-over phases of the accident, but do not protect against secondary impacts with the ground or other roadside objects. Therefore, depending on how many of the target population of fatalities result from the secondary impact, the estimates used could be subject to a degree of error.

Furthermore, the cost evidence is limited and applies only to the costs for one measure: the enhanced 'safety bar'. Changes to add a nosecone may be greater than these estimates; no suitable figures were found in the course of this study, but it is considered that a proportion of these costs could have no net increase over and above costs for new model upgrades if synchronised with manufacturer's existing design cycles.

5.3 Regulatory Considerations

The impact performance of enhanced TFEDs could be achieved by adapting the Heavy Vehicles Aggressively Index (HVAI) developed during the APROSYS project (Smith, 2008). Whilst much of the HVAI could be directly applied, several compatibility issues between the protocols developed by Smith *et al.* and HGVs with enhanced TFEDs have been identified by this project. Such revisions could be added to Regulation 78 which does not currently cover HGVs but consideration would need to be given regarding how requirements might change with the fitment of AEBS.

Nosecone designs will dictate that updates to the HVAI are made because the structural index of the HVAI was proposed based on flat front designs and the test area was defined based on this assumption. The run-over index was also defined with the cab edges and frontal areas based on current, vertical-faced truck geometries. Consequently, testing approaches would need to be redesigned to ensure that they appropriately assess enhanced TFEDs that incorporate nosecone geometries. Numerical simulation could be used to minimise the physical testing costs and this could be combined with a 'spot check' philosophy for any testing carried out.

6 Front Underrun Protection

6.1 Technical Considerations

6.1.1 Background on safety measure

Front Underrun Protection [FUP]

The front underrun protection safety measure considered within this project concerns the structural components located at the front end of the HGV that optimises opponent compatibility, prevents underrun events and ensures the occupant survival space during frontal collisions involving passenger cars.

Front underrun protection (FUP) was originally intended to correct a fundamental impact incompatibility between passenger cars and HGVs in head-on collisions. HGVs are much heavier than cars, with stiffer structural components and are positioned higher from the ground. In head-on collisions, the 'crumple zone' at the front of the car will typically pass underneath the front of the HGV without deforming and absorbing energy as intended. The rigid chassis of the HGV will interact with the top of the car engine and the A-pillars, causing extensive intrusion into the car with a consequential increase in injury risks. This is illustrated by the real-world collision shown in Figure 10 below.

Figure 10: Example of a head-on collision resulting in underrun.

In 2003, the EU implemented the requirements of UNECE Regulation 93 as a mandatory part of type approval for HGVs (UNECE, 1994). This required front underrun protection that placed stiff structures across the front of an HGV at heights no greater than 400 mm from the ground, with the intention to prevent the type of gross underrun illustrated in Figure 10. Knight (2016) found that, although there was comprehensive evidence to support the introduction of this measure, there was very little scientific study of its actual performance after implementation. The evidence that was identified did not show the anticipated positive beneficial effect on the number of car occupant casualties. While this might be because other factors confounded the relatively simplistic analyses undertaken, such that these findings represented an 'absence of evidence' about the effect, there remained a possibility that the intended effect may actually be absent.

The analyses by Knight (2016) summarised several possible reasons for this:

- Structural interaction: Evidence was presented to show that, while complete underrun was often prevented by FUPS in compliance with R93, structural interaction could still be quite poor resulting in the crashworthiness structures of cars not working properly in collisions with HGVs. Problems included poor alignment of structures both vertically and horizontally and mismatches in component stiffness;
- Speed: head-on collisions between cars and HGVs often occur at high speeds, with only around 10% of fatalities involving closing speeds at or below the Euro NCAP test speed (64 km/h). Over 80% involve closing speeds in excess of 100 km/h, with these high speeds leading to a requirement for an additional HGV crumple zone to absorb a greater proportion of energy during the collision.

6.1.2 Opportunities for enhanced TFEDs

Opportunities exist for improvements in the structural interaction of FUPS in the existing length limits for traditional HGVs. Increasing the size of the cross members, so that they cover more of the area under the front of the HGV, would increase the likelihood of the FUP interacting directly with the diverse range of crashworthiness structures adopted by the passenger cars on the market. Harmonising on a common interaction zone between cars and HGVs would be beneficial. Similarly, increasing the bending stiffness of the beam would help to reduce the 'fork effect' that can occur when the two stiff longitudinal members of a car impact the FUP either side of the stiff vertical support, resulting in the forming of undesirable load paths (e.g. FUP support bracket to car engine).

In theory, there is up to ~400mm of space available underneath the front of a traditional HGV in which controlled deformation of the FUP could be permitted to absorb energy and act as a 'crumple zone'. In practice, however, it was found that this deformation space was actually only ~250 mm, as other stiff structures located in the front end of the HGV (e.g. tow hooks etc.) could form alternative loading paths with the car (e.g. with the car engine) to limit the deformation of the FUP (Edwards *et al.*, 2007). In addition to this, it was also hypothesised that the stiffness and energy absorption capability of the front end cars had increased to the extent that the additional capacity offered by the ~250 mm of FUP represented only a small fraction of the total energy absorbed.

The energy absorbed by the crumple zone is directly related to the stiffness at which the structure deforms and the distance by which it is deformed. The stiffness of a FUP will, therefore, also be dictated by the stiffness of the range of passenger cars on the market. If the FUP has a low stiffness, the quantity of energy absorbed will be low, particularly in relation to protecting larger heavy cars. If the FUP stiffness is high, the passenger cell of a car may begin to deform before the FUP does, which is a particular problem for smaller lighter cars. With the range of acceptable stiffness values limited, increasing the energy absorption capacity via increased deformation lengths is the only remaining option.

HGVs with enhanced TFEDs that extend the cab length provide an option to increase the deformation length available for FUP devices. This would increase the energy absorbing capacity of the HGV, decreasing the proportion of the total collision energy absorbed by the car. Put another way, it greatly increases the 'ride-down' distance available to the car, reducing the peak accelerations experienced by cars when compared to a situation where the crumple zone of the car 'bottoms out' and the passenger cell began to deform. Thus, the integration of an energy absorbing FUP device, with an extended deformation range, has the potential to enhance the protection offered to car occupants during head-on collisions with HGVs at high closing speeds.

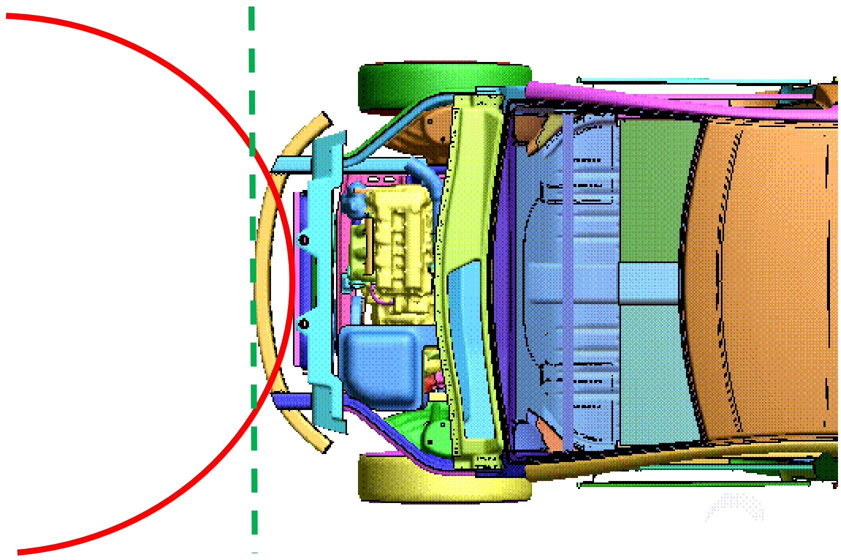


Figure 11: Schematic illustrating possible interaction of curved FUP (red) with car structure at moment contact is made with car longitudinals (Knight, 2016)

It must be noted, however, that good structural interaction is also a pre-requisite of good energy absorption. It is likely, therefore, to be necessary to implement a range of new requirements, in relation to the structural interaction ability of enhanced TFEDs with cars, to ensure the predicted benefits of energy absorption are achieved. It can be seen that, depending on impact configuration, a curved FUP could interact adversely with the engine compartment of the car (Figure 11) or introduce non-axial loading (Figure 12) into the crashworthiness structures of the car which they are not necessarily designed to absorb. These situations can potentially be avoided by using a flat FUP across most of the vehicle width, but positioned further to the rear (Knight, 2016). The structures ahead of the FUP must then, however, all provide negligible impact resistance to a colliding car, which may limit the opportunity for packaging a variety of important components.

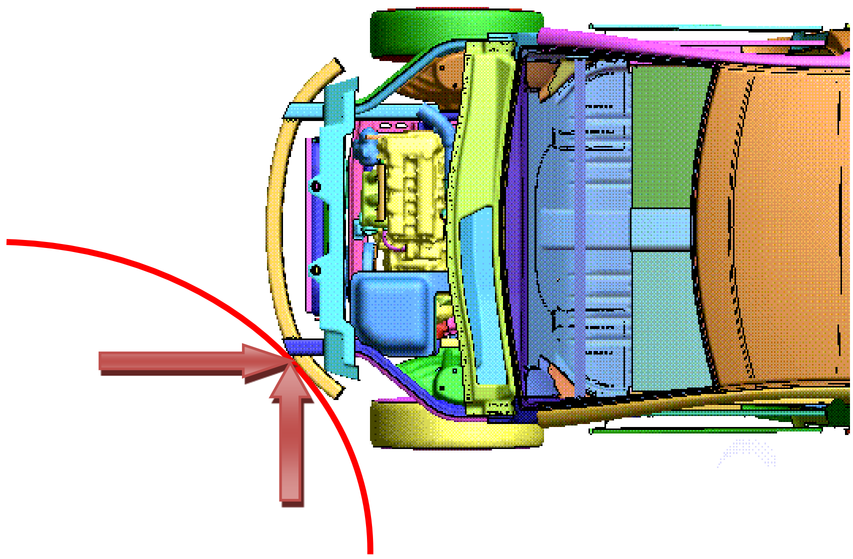


Figure 12: Schematic illustrating potential deflection effect of a curved FUP in an offset collision (Knight, 2016)

6.1.3 Possible overlaps in benefits and technology

The design of HGV cabs is a complex compromise between a range of competing factors, including the aerodynamics, manoeuvrability, mass distribution and packaging of a HGV, in addition to the safety measures reviewed by this project. The effect of regulating the FUP performance of enhanced TFEDs may influence a range of factors, including both those considered in scope for this particular project and those considered as out of scope.

The FUP is a mechanical structure that directly targets the protection of car occupants in head-on collisions and so does not have much scope for influencing the other types of casualty investigated by this project. Despite this, there are potentially some additional benefits to those injured in collisions between the front of the truck and the rear or side of a car. These opportunities will likely be small, however, because those areas of a car are not designed with large crumple zones in the same way as the front. Thus, there are limited overlaps in target populations and benefits.

When considering effectiveness, there are potentially areas of design trade-offs between good front underrun protection and other safety measures. Increasing FUP performance through increased length has already been linked to manoeuvrability limitations including both cornering and ground clearance limitations. Maximising this performance may also impact the protection of VRUs, as utilising a greater proportion of the cab extension for FUP will reduce the design space available for integrating VRU impact protection [VIP]. Finally, when considering designing a HGV to maximise occupant protection, the crumple zones to protect occupants would need to be considerably stiffer and located at a greater distance from the ground than a FUP. There may, therefore, also be a trade-off between maximising FUP benefits and maximising benefits for improved HGV occupant protection.

When considering the influence of competing factors outside of the five safety measures investigated by this project, it is clear that many of the measures that were proposed by the General Safety Regulation review could also influence the target populations affected by indirect vision performance requirements (Seidl *et al.*, 2017). This could include driver assist or active safety devices including: autonomous emergency braking for pedestrians and cyclists [AEBS-PC], lane keep assist [LKA], intelligent speed assist [ISA] and driver drowsiness and distraction recognition [DDR] devices.

To address this issue within the scope of this project, it is important to ensure that, when adapting any future regulation for enhanced TFEDs, the regulatory requirements consider the potential effects of likely cab designs on regulating front underrun protection (FUP) performance. This is especially important when considering regulating both VRU and cab occupant protection.

6.2 Potential Effects of Regulation

6.2.1 Target population

The annual target populations estimated for both fatally and seriously injured casualties relevant to the front underrun protection safety measure are shown below in Table 20. These target populations have been calculated for passenger car occupants, as this is the only population affected by improvements in FUP performance. The selection of an appropriate target population range was performed to include all HGV collisions that involved car occupants during head-on collisions. Data from Robinson and Chislett (2010) was used to estimate the proportion of fatal collisions, whilst the Volvo Trucks (2013) and Welfers *et al.* (2011) studies estimated the ranges for serious injuries (Annex 1.3.3).

Table 20: Estimated annual target populations for the front underrun protection [FUP] safety measure and comparing both the differentiated and uniform approaches

	Uniform (*n*)			Differentiated (*n*)		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Car Occupants	674	1220-2247	1894-2921	340	615-1132	955-1472

6.2.2 Estimates of effectiveness

The overall effectiveness values estimated for fatally and seriously injured casualties that were relevant to the FUP safety measure are shown below in Table 21. For the purposes of estimating the overall effectiveness of the FUP safety measure, both the current best-in-class and mid-range performance levels were selected. These two effectiveness levels were selected to provide a comparison of costs and benefits for two key scenarios: the entire cab length extension being used for the FUP device and the cab length extension being used for a combination of FUP and VIP devices.

Table 21: Estimated overall effectiveness of the best-in-class and mid-range designs for the front underrun protection [FUP] safety measure

	Best-in-Class TFED Extension (0.8 m)		Mid-Range TFED Extension (0.4 m)	
	Fatals (%)	Serious (%)	Fatals (%)	Serious (%)
Car Occupants	10-27	55-65	6-17	45-60

Knight (2016) summarised research examining the distribution of closing speeds during head-on collisions and considered different vehicle length increases in the range of 200 to 800 mm. This study found that 5-27% of fatalities and 40-67% of serious injuries were in scope for protection by energy absorbing FUPs (Knight, 2016). When considering designs providing best-in-class protection, energy absorbing FUPs were found to be capable of preventing 10-27% of fatalities and 55-65% of serious injuries. When considering mid-range levels of protection, however, energy absorbing FUPs could potentially prevent only 6-17% of fatalities and 45-60% of serious injuries (Knight, 2016).

6.2.3 Cost implications

The costs of compliance with energy absorbing FUP performance levels as part of a type-approval process for HGVs with enhanced TFEDs can be divided into two categories:

1. Differences in development, manufacturing and approval costs due to the addition of the regulated feature
2. Differences in operational, environmental and infrastructure costs due to changes in the vehicle mass or payload

Very little objective and accurate information is available on the likely costs associated with requiring enhanced front underrun protection for a revised front-end design when compared to revising the front end design without the enhanced FUP requirements. The estimate below in Table 22 is derived from Knight (2014), which calculated the additional costs for introducing energy absorbing FUP systems.

Table 22: Estimated costs per vehicle and total fleet costs of the best-in-class designs for the front underrun protection [FUP] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Costs (€/vehicle)	220-350	220-350
Total Fleet Costs (€Bn)	1.42-2.25	0.81-1.30

These estimates relate only to the cost headings included in item 1 above. Knight (2014) estimated that revisions to cross members and the addition of longer energy absorbing structures could conceivably add 100 kg to the mass of a truck. Robinson *et al.* (2010) modelled the journey cost generation effect of adding a mass of between 125-250 kg as a consequence of an enhanced TFED and showed that at the upper end of that range the costs outweighed the benefits. Accurately modelling journey cost generation effects is, however, extremely complex and sometimes controversial and so is not included here.

6.2.4 Cost effectiveness summary

Table 23 below summarises the estimated annual casualty reduction benefits that would be expected by regulating the FUP performance of HGVs with enhanced TFEDs to either the best-in-class or mid-range levels. These values are then monetised to provide estimates of the monetary benefits of the casualty reductions to the EU, with the mid-range TFED extensions sharing the benefits with the mid-range VIP safety measure.

Table 23: Estimated annual casualty reduction benefits of the best-in-class and mid-range designs for the front underrun protection [FUP] safety measure and comparing both the differentiated and uniform approaches

	Uniform			Differentiated		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Best-in-Class TFED Extension (0.8 m)						
Casualty Reduction (*n*)	67-182	671-1461	738-1643	34-92	338-736	372-828
Monetised Benefits (€M)	105-285	155-338	261-623	53-143	78-170	131-314
Mid-Range TFED Extension (0.4 m)						
Casualty Reduction (*n*)	40-115	549-1348	589-1463	20-58	277-679	297-737
Monetised Benefits (€M)	63-179	127-312	190-491	32-90	64-157	96-247

Finally, Table 24 provides estimates for the break-even costs and benefit-cost ratios over a 10-year time period according to the differentiated and uniform approaches, with the mid-range TFED extensions sharing both the costs and benefits with the mid-range VIP safety measure.

Table 24: Estimated 10-year break-even costs and benefit-cost ratio per vehicle of the best-in-class and mid-range designs for the front underrun protection [FUP] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Best-in-Class TFED Extension (0.8 m)		
Break-Even Costs (€/vehicle)	405-966	355-848
Benefit-Cost Ratio	**1.16-4.39**	**1.01-3.85**
Mid-Range TFED Extension (0.4 m)		
Break-Even Costs (€/vehicle)	295-762	259-669
Benefit-Cost Ratio	*0.84-3.47*	*0.43-1.67*

6.2.5 Assessment of evidence

The level of evidence underpinning the potential benefits of regulating the front underrun protection performance of HGVs with enhanced TFEDs is of a good standard. It has involved rigorous accident analyses, experimental programmes and extensive computer simulations, often in partnership with manufacturers, over many years. The engineering theory supporting extended 'nosecones' on vehicles is also sound, however, the body of physical test and computer simulation work explicitly studying this option is smaller and concerns have been expressed regarding the real-world performance of longer, energy absorbing, structures, particularly in angled impacts.

The evidence base that predicts FUP effectiveness is of a lower level. Post-hoc analyses of the effect of introducing rigid FUP devices are extremely limited. Predicted effects of changes are based principally on theoretical calculations of equivalent energy speeds and distributions of collision speeds taken from 10 year-old collision data. Importantly, this data did not account for either casualty age or seat belt use, which were both shown to be significant factors in fatal collisions (Robinson *et al.*, 2010). As these factors were not explicitly included, the previous figures may, in fact, over-estimate the casualty reduction benefits of FUP devices.

It should also be noted that energy absorbing FUP devices are principally targeted at high speed, high energy collisions. It is, therefore, relatively unlikely to mean that a fatality would be mitigated to the extent that they would be uninjured. After such a collision, the casualty may still remain seriously but not fatally injured. This injury cascading effect has not, however, been reliably quantified by any source and so, in the absence of evidence, this report assumes that all fatalities and serious injuries are entirely mitigated. This, of course is, again, likely to over-estimate the casualty reduction benefits of FUP devices.

When considering the target population estimations, only three studies provided a high enough level of evidence to characterise the proportion of head-on collisions between HGVs and cars (Robinson and Chislett, 2010;Volvo Trucks, 2013;Welfers *et al.*, 2011). Values for fatalities were extracted from Robinson and Chislett (2010), although this was the only study providing figures on fatal collisions alone, so no ranges could be extracted. Welfers *et al.* (2011) provided values from three European collision databases, including several manufacturer collected database, whilst the Volvo Trucks (2013) report provided an analysis of collisions from several different European collision database. Both studies failed to segregate outcomes between fatal and serious injuries, whilst neither provided any further context as to how data had been collected by the referenced databases. The use of these values to estimate target populations, however, uses the best available evidence. Further collision analyses to refine these values are therefore recommended.

The evidence related to cost is also limited. No equivalent structures are on the market anywhere and no prototypes matching the proposed requirements are yet known to exist. Past estimates have been based on asking industry about one-off development costs and applying estimates of cost per kg of material.

Future publications that may better support the above estimations with a higher level of evidence are expected soon. A report from ACEA is expected to provide estimations of target populations that are highly relevant to the FUP safety measure and will be based on data from both national and in-depth collision databases. This will be supported by the release of the Volvo Trucks Accident Research Team safety report that will provide target population data based on the analysis of a number of international, national and in-depth collision analysis databases.

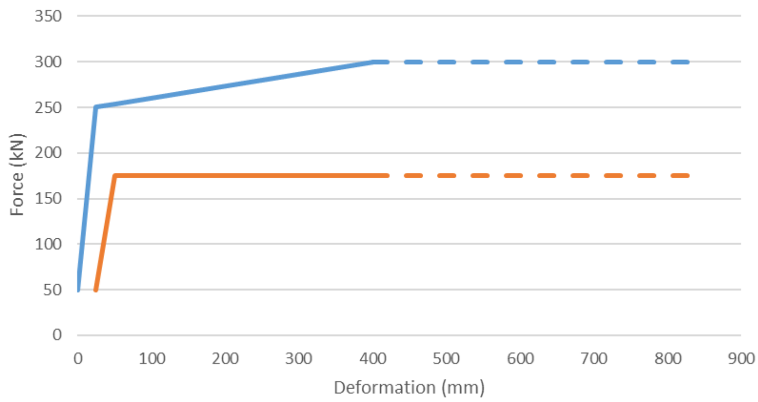
6.3 Regulatory Considerations

When considering regulating the FUP performance of enhanced TFEDs it is clear that any requirements should be underpinned via the adaptation of Regulation 93. Whilst much of R93 should remain unchanged, several compatibility issues between R93 and HGVs with enhanced TFEDs have been identified. Currently, R93 is written based on an existing flat front, cab over engine, design. It limits the crush of a FUP to a maximum displacement of 400 mm and this could only be achieved via FUPs with a curved profile. The test method used to prove FUP compliance, however, would not currently be appropriate for FUPs with curved profiles.

Knight (2016) proposed a range of options with the potential to solve these problems:

- Quasi-static tests combined with design requirement
- Mobile Progressive Deformable Barrier test combined with design requirements
- Purpose designed deformable barrier test combined with design requirements

Quasi-static tests would be similar to those currently undertaken and could only be used with a straight FUP cross-member. It was proposed that the existing minimum force and maximum deflection criteria are changed to a requirement for a force-deflection curve to fall within a corridor representing compliant stiffness levels, with a minimum requirement for energy absorbed, based on the distance the manufacturer chose to exceed standard length limits (Figure 13).



Deformation (mm)	Force (kN)	
	Upper	Lower
0	50	
25	250	50
50	254	175
400	300	175
400	300	175
850	300	175

Figure 13: Proposed force-deflection corridor for quasi-static test (Knight, 2016)

If curved FUP devices are adopted by HGVs with an enhanced TFED, dynamic tests are proposed where a mobile deformable barrier (MPDB) collides with a FUP sub-assembly at speeds depending on manufacturer requested length extensions (Table 25). The barrier could potentially be the MPDB defined for passenger car tests or, if unsuitable, a bespoke barrier designed for the purpose.

Table 25: Proposed mobile deformable barrier test speeds based on requested length extension (Knight, 2016)

Length extension (mm)	Deformation length available (mm)	Proposed test speed (km/h)
0-200	200-400	70
201-400	400-600	80
401-600	600-800	85
601-800	800-1000	90

These proposals were, however, based on engineering theory alone and may therefore require extensive physical testing with near production prototypes in order to optimise and validate the proposals in detail.

7 Vulnerable Road User Airbags

7.1 Technical Considerations

7.1.1 Background on safety measure

VRU Airbag [VAB]

The vulnerable road user airbag safety measure considered by this project concerns the assistive device that detects or predicts the occurrence of a VRU collision to trigger and deploy an airbag to protect VRUs during impact.

There are three potential phases to collisions between HGVs and VRUs; a primary phase where the VRU impacts the HGV, secondary impacts with the surrounding infrastructure or road surfaces and the potential over-run of the VRU by the HGV. VRU airbags will only have the potential to mitigate injuries during the primary impact phase, as these inflate to mitigate the energies transferred to the body, and in particular the head, during an impact against the front end of the HGV. Once the airbag has been inflated and impacted it no longer offers its designed level of protection and so cannot therefore be used for the mitigation of further impacts.

Airbags are typically inflated during a collision by penetrating a pressurised gas cartridge by a trigger to inflate an airbag contained within the structures of the vehicle. Typical airbag intervention times, including the activation, triggering and inflation of the airbag, are typically around 50 ms, depending upon the model. Activation times, defined as the time between the point at which a collision becomes inevitable and the activation of the triggering mechanism, vary significantly between different models and collision scenarios. Once activated, typical trigger times, defined as the time between activating the trigger and penetrating the gas canister, are usually very short in duration. Airbag inflation times can then also range widely, with this dependent on the size and pressure requirements of the particular airbag. Finally, airbag deflation times, defined as the time taken for airbag pressures to reduce below a minimum operating pressure, can also range widely between models and typically lasting for between 5 and 30 seconds of effective inflation.

Although providing a form of advanced secondary safety system, the VRU airbag safety measure is considered separately from the VRU impact protection safety measure. This is because of the sensor activation requirements for this system and because the expected benefits for a successfully deployed and impacted system would far exceed that expected for the more passive VRU impact protection safety measure (Jakobsson *et al.*, 2013). The performance of the airbag is, however, dependent upon a number of factors including the VRU kinematics during impact, the coverage of the airbag, the system intervention times and the head impact timing, all of which can affect a successful outcome.

Detailed regulatory requirements for VRU airbags are, however, not explicitly defined for vehicles. Although the pedestrian safety performance of passenger cars is regulated via R127, with no such equivalent regulation for HGVs (see Section 5), this regulation does not specify that passenger cars should implement an external airbag. A similar approach is taken for internal occupant airbags, where the requirement for an airbag is implicitly defined based on requirements for vehicles to comply with stringent performance criteria that oblige manufacturers to use an airbag. An alternative approach could therefore be to extend the APROSYS Heavy Vehicle Aggressivity Index (HVAI) (Annex 2.8.1) approach to provide a range of more stringent requirements for regulating VRU impact performance in key zones that obliges manufacturers to install external airbags to ensure compliance.

7.1.2 Opportunities for enhanced TFEDs

VRU airbags are currently available on a number of passenger cars to provide enhanced protection around the windscreen, scuttle and A-pillars of the car. VRU airbags for HGVs were also proposed within the APROSYS project; however, no such devices have entered production in practice. A key reason for this is the current adoption of cab-over-engine designs, as these mean that HGVs require expensive sensor solutions to predict impacts to the front of the HGV to allow enough time for the airbag to inflate before the VRU is impacted. A key metric used to assess this is the wrap around time, which is the time taken from the moment of first impact to the moment that the head of the VRU impacts the vehicle. This key metric is, in general, much larger for current passenger car designs than for cab-over-engine design HGVs.

When considering HGVs with enhanced TFEDs, it is clear that the inclined and curved face of the cab could offer an opportunity to mount an airbag, whilst still allowing enough time for the deployment of the airbag before the head of the VRU impacts the HGV structures. The adoption of inclined or curved faces will provide additional distance between the VRU and the HGV structures, which would not exist with current HGV designs, with this extra distance being used to allow sufficient time for deployment of the airbag. An appropriate distance could be 400 mm at head height, which, if assuming that airbag intervention times are 50 ms, would mean that airbags would inflate to their operational pressures for all collisions with VRUs at impact speeds of <28.8 km/h. Based on an analysis by Schreck and Seiniger (2014), this relative impact speed would include 99% of cyclist collisions.

The coverage that the airbag provides could also range from full to partial coverage. Full coverage airbags covering the whole HGV front end may not be the most cost-effective solution, whilst an airbag that partially covers the nearside and offside edges of the HGV only could perhaps be the more effective solution. For the purposes of this review, it was therefore assumed that the VRU airbag safety measures would only investigate airbags that partially cover the nearside and offside edges of the front end of the enhanced TFED.

7.1.3 Possible overlaps in benefits and technology

The effect of regulating the VRU airbag performance for enhanced TFEDs may influence a range of factors, including both those considered in the scope of this particular project and those considered out of scope. When considering the five safety measures reviewed in this project, regulating enhanced TFEDs to improve VRU airbag performance is likely to influence the target population of the VRU impact protection [VIP] safety measures only. It is also clear that a range of sensors could be used to activate the airbag. These can be mechanical triggers, which activate when contact is first made with the VRU, and sensor-based systems, such as ultrasonic, LIDAR and RADAR sensors or cameras, which activate the VRU airbag when the collision becomes unavoidable, but prior to the collision actually occurring. The costs of these sensors may therefore be shared with other systems, with this particularly affecting the indirect vision camera [CAM] safety measure in this project.

When considering the influence of competing factors outside of the five safety measures investigated by this project, it is clear that many of the measures that were proposed by the General Safety Regulation review could also influence the target populations affected by indirect vision performance requirements (Seidl *et al.*, 2017). This could include driver assist or active safety devices including: autonomous emergency braking for pedestrians and cyclists [AEBS-PC], lane keep assist [LKA], intelligent speed assist [ISA] and driver drowsiness and distraction recognition [DDR] devices. It is also clear that the LIDAR and RADAR sensors used to trigger the AEBS-PC devices may also be utilised by VRU airbags.

To address this issue within the scope of this project, it is important to ensure that, when adapting any future regulation for enhanced TFEDs, the regulatory requirements consider the potential effects of likely cab designs, and VRU impact protection regulations, on the regulation of VRU airbag performance.

7.2 Potential Effects of Regulation

7.2.1 Target population

The annual target populations estimated for both fatally and seriously injured casualties relevant to the vulnerable road user airbag safety measure are shown below in Table 26. These have been calculated for pedestrians and cyclists, as these are the two populations primarily affected by improvements in HGV VRU airbag performance. The selection of an appropriate target population range was performed to include all collisions involving VRUs impacting the front end of the HGV. Robinson *et al.* (2016) and Robinson and Chislett (2010) were used to estimate the proportion of fatalities, whilst studies by Summerskill *et al.* (2017) and Robinson and Chislett (2010) estimated the ranges for serious injuries (Annex 1.3.3). It is important to note that it was not possible to estimate the proportion of VRUs injured during primary or secondary impacts or during run-over impacts.

Table 26: Estimated annual target populations for the VRU airbag [VAB] safety measure and comparing both the differentiated and uniform approaches

	Uniform (n)			Differentiated (n)		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Pedestrians	401-415	92-104	493-519	120-124	102-128	222-252
Cyclists	339-426	225-256	564-682	28-31	68-77	96-108
Total	740-841	317-360	1057-1201	148-155	170-205	318-360

7.2.2 Estimates of effectiveness

The overall effectiveness values estimated for fatally and seriously injured casualties that were relevant to the VRU airbag safety measure are shown below in Table 27. For the purposes of estimating the overall effectiveness of the VAB safety measure, the current best-in-class performance levels for pedestrian airbags were selected. To calculate the total effectiveness of VRU airbags the technology effectiveness was combined with both an airbag coverage factor and a sensor activation factor.

Technology effectiveness values for fatal collisions were sourced from de Hair-Buijssen, (2010) whilst the technology effectiveness values for serious collisions were sourced from Fredriksson and Rosen (2014) and Fredriksson *et al.*, (2015). All technology effectiveness values were, however, based on studies involving pedestrian and cyclists impacting VRU airbags installed on passenger cars. Sensor activations factors were selected to be 100% based on the assumption that the activation system for a best-in-class sensor would use a mechanical trigger and that the VRU head would travel over 400 mm before impacting the HGV structures. Finally airbag coverage factors were applied based on an in-depth analysis of impact points for VRUs (Annex 1.3.5), where 50% of pedestrians and 47-53% of cyclists were found to impact the nearside and offside front corners of the HGV.

Table 27: Estimated overall effectiveness of the best-in-class technology for the VRU airbag [VAB] safety measure

	Fatals (%)	Serious (%)
Pedestrians	18-22	15-23
Cyclists	9-26	13-20

7.2.3 Cost implications

The costs associated with installing a VRU airbag can be seen in Table 28 and are based on estimations of the cost of a VRU airbag for a car by Seidl *et al.*, (2017). To account for the larger airbag sizes that would be required for a HGV this cost was doubled. Costs will vary between a mechanically activated and a sensor activated system and there could be potential for the sensors to be used for dual purposes which may be more cost beneficial. These costs were then multiplied by the total number of both HGVs and articulated trucks in the fleet to provide the total cost to industry when considering both the differentiated and uniform approaches (Table 28).

Table 28: Estimated costs per vehicle and total fleet costs of the best-in-class technology for the VRU Airbag [VAB] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Costs (€/vehicle)	170-340	170-340
Total Fleet Costs (€Bn)	1.10-2.19	0.63-1.26

7.2.4 Cost effectiveness summary

Table 29 below summarises the estimated annual casualty reduction benefits that would be expected by regulating the VRU airbag performance of enhanced TFEDs to the best-in-class level. These values are then monetised to provide an estimate of the monetary benefits of the casualty reductions to the EU.

Table 29: Estimated annual casualty reduction benefits of the best-in-class technology for the VRU Airbag [VAB] safety measure and comparing both the differentiated and uniform approaches

	Uniform			Differentiated		
	Fatals	Serious	KSI	Fatals	Serious	KSI
Casualty Reduction (n)						
Pedestrians	72-91	51-98	123-189	22-27	15-29	37-56
Cyclists	8-27	30-52	38-79	2-8	9-15	11-23
Total	80-118	81-150	161-268	24-35	24-44	48-79
Monetised Benefits (€M)						
Pedestrians	113-143	12-23	125-165	34-43	4-7	37-50
Cyclists	13-42	7-12	20-54	4-13	2-4	6-16
Total	126-185	19-35	144-219	38-55	6-10	43-66

Finally, Table 30 provides estimates for the break-even costs and benefit-cost ratios over a 10-year time period according to the differentiated and uniform approaches.

Table 30: Estimated 10-year break-even costs and benefit-cost ratio per vehicle of the best-in-class technology for the VRU airbag [VAB] safety measure and comparing both the differentiated and uniform approaches

	Uniform	Differentiated
Break-Even Costs (€/vehicle)	224-340	117-178
Benefit-Cost Ratio	*0.66-2.00*	*0.34-1.05*

7.2.5 Assessment of evidence

The level of evidence currently evaluating the potential benefits of VRU airbags for HGVs with enhanced TFEDs is low. Although several studies have assessed the effectiveness of external VRU airbags, these have all compared airbag performances for passenger cars only. It therefore remains unknown as to how effective enhanced TFEDs actually may be in reducing casualties through this approach.

Of the studies evaluating the effectiveness of VRU airbags, none were found to provide empirical evidence that directly related the installation of VRU airbags on HGVs with the mitigation of injury severities. The only studies that provided such evidence were found to establish the effectiveness of VRU airbags for passenger cars only (de Hair-Buijssen *et al.*, 2010;Fredriksson and Rosen, 2014;Fredriksson *et al.*, 2015), resulting in an indirect relationship only. More relevant research is therefore required to provide evidence that specifically answers this particular research question.

When considering the estimation of the target populations, only three studies provided a high enough level of evidence to characterise collisions between HGVs and VRUs by point of impact (Robinson *et al.*, 2016;Robinson and Chislett, 2010;Summerskill *et al.*, 2017). Another two studies that provided similar evidence were eventually excluded based on the results not being generalizable enough to provide information regarding the overall European collision landscape, as they were based on a small selection of collisions in London only (Knowles *et al.*, 2012;Talbot *et al.*, 2014).

Values for pedestrian and cyclist fatalities were extracted from Robinson *et al.* (2016), with values for serious injuries were extracted from both Robinson and Chislett (2010) and Summerskill *et al.* (2017). Whilst Robinson *et al.* (2016) investigated fatalities only, Summerskill *et al.* (2017) did not separate results between the injury severity levels (i.e. presenting values for all injuries). Unfortunately, all three studies also provide collision data from Great Britain, whilst also failing to differentiate between collisions that involve a run-over incident which could result in an over-estimation of the target population. The use of these estimated target populations, however, uses the best available evidence base. Further collision analyses to refine these values are therefore recommended.

Finally, the evidence base related to costs has been based on the values agreed with industry stakeholders during the General Safety Review consultation (Seidl *et al.*, 2017). As these costs were related to the costs of a VRU airbag system for passenger cars, the costs were doubled to account for the greater areas of coverage that would be required for HGVs with enhanced TFEDs. No relevant airbags were found to be on the market, nor have any working prototypes been developed for HGVs. A more specific stakeholder consultation with industry could therefore be appropriate for agreeing on the extra costs associated with requiring best-in-class external VRU airbags.

Future publications that may better support the above estimations with a higher level of evidence are expected soon. A report from ACEA is expected to provide estimations of target populations that are highly relevant to the VAB safety measure and will be based on data from both national and in-depth collision databases. This will be supported by the release of the Volvo Trucks Accident Research Team safety report that will provide target population data based on the analysis of a number of international, national and in-depth collision analysis databases.

7.3 Regulatory Considerations

When considering regulating the FUP performance of enhanced TFEDs it is clear that any requirements should be underpinned by adapting the Heavy Vehicles Aggressivity Index (HVAI) developed during the APROSYS project (Smith, 2008). Whilst much of the HVAI should remain unchanged, several compatibility issues between the protocols of the HVAI and HGVs with enhanced TFEDs have been identified by this project.

As the structural index of the HVAI was proposed based on existing flat front, cab-over-engine, designs, it limits the testing area to a grid defined based on the assumption that the front-end of the cab is both flat and perpendicular. A similar issue is experienced for the run-over index of the HVAI, which defines the cab edges and frontal areas based on a similar cab-over-engine design. These testing approaches would need to be reassessed to ensure that they are compatible for HGVs with enhanced TFEDs. Importantly, as such HGV designs are likely to adopt inclined faces, any updates to the HVAI will have to take into consideration the wrap around distances of the VRU.

When considering the specific issue of testing VRU airbags, the pass/fail criteria adopted for the head impact testing could be set at a lower HIC value than 1000. By providing a more stringent performance criterion, perhaps focussed on the front nearside and offside corners, this could encourage manufacturers to install airbags that better protect the VRU during impacts with HGVs in these specific areas. One further issue noted with the HVAI, if generally applied to all HGVs, was the lack of testing at lower impact speeds. Whilst the upper range of the impact speeds relate to the upper speeds of collisions between HGVs and cyclists, lower speed impacts also occur between HGVs and pedestrians during low speed manoeuvres. Whilst the HVAI currently tests for high energy impacts at impact speeds of 11 m/s, future amendments may wish to also test at lower speeds of 1.5 m/s, as this represents the average walking speed of a pedestrian (Gates *et al.*, 2006).

8 Primary Active Safety Measures Overview

Primary Active safety measures are not directly in scope of this project, partly because they are not directly linked to the opportunity for exploiting the additional cab lengths permitted as part of an enhanced TFED. However, as part of the drive towards increasingly automated vehicles, which many commentators predict will be available on HGVs in some form within the next decade, active safety technologies are proliferating rapidly. In many cases, these have the potential to offer safety benefits to the same groups of casualties targeted by the TFED measures that are in scope. This section aims to give an overview of the technologies available now, and in the near future, to provide a discussion of the relative effectiveness of different active safety measures, where various safety measures can complement each other and where they 'compete' for the same target populations. It should be noted that this is not an exhaustive study of all such technologies.

8.1 Vulnerable road users

8.1.1 Crossing collisions

The most important mechanism for pedestrian collisions with HGVs occurs whilst crossing the road in front of HGVs moving at normal urban traffic speeds (Annex 1.3.3.2). Cyclists are also injured via similar mechanisms, though this often involves a collision at the front of the HGV at a junction, specifically where the HGV enters the junction while the cyclist crosses in front of it. As previously discussed in Section 5, an enhanced TFED provides an opportunity to improve injury outcomes in these cases by redesigning and softening the front-end of the vehicle to both reduce collision forces and improve VRU kinematics to reduce the likelihood of being subsequently run over by the wheels of the HGV.

A range of research has shown that these crossing collisions are usually characterised by very short available reaction times for the driver (mostly under 2 seconds) regardless of the HGV type involved (Knight and Avery, 2015;Grover *et al.*, 2013). Although improved direct vision designs and indirect vision devices, such as cameras and sensor-based detection systems, are expected to improve the outcomes of these types of collision, the extent to which these safety measures can affect this particular collision type is limited. This is primarily due to the driver not being able to react to the incident in enough time to successfully avoid the collision, regardless of whether the driver was, in fact, already alert and aware of the potential risks.

Automated Emergency Braking (AEB) systems that work in collisions where pedestrians cross in front of the vehicle are widely available on passenger cars, with Euro NCAP test results showing that a large proportion of models tested since the introduction of the test in 2016 have AEB installed (Euro NCAP, 2017). AEB systems can be effective as they can react in as little as around 0.3 seconds to apply the brakes, much faster than the range of 0.75 to 2 seconds typically considered for a normal population of drivers. Grover *et al.*, (2013) showed that the best systems could fully avoid collisions at speed of up to around 50 km/h when collisions occur in the central part of the vehicle (when measured between 25% and 75% of the vehicle width). To avoid false positives, however, vehicles typically only apply the brakes once the VRU is directly in the path of the vehicle. AEB systems are therefore considered less effective for collisions that occur at the edges of the vehicle.

A number of studies have shown that approximately 50% of both pedestrian and cyclist collisions occur towards the front-nearside and front-offside edges of HGVs (Annex 1.3.5) (Robinson *et al.*, 2016;Talbot *et al.*, 2014;Schreck and Seiniger, 2014;Knowles *et al.*, 2012). Robinson and Chislett (2010) found that one-third of pedestrians killed in crossing collisions were struck by HGVs travelling at less than 40 km/h. Although car systems can be effective at up to 50 km/h, there are a number of factors specific to HGVs that might limit their effectiveness. For example, the pneumatic parts of the braking system will lead to slightly longer brake build up times than for hydraulic systems on cars and the heavier duty tyres and efficiency of the brakes and ABS may limit the maximum deceleration that can be achieved by the HGV. This may limit the maximum speed from which a collision is avoidable in comparison to cars.

However, even if this limitation reduces the maximum avoidance speed to 40 km/h, it is clear that a substantial proportion of fatalities will be in scope. At speeds in excess of 40 km/h, the system may not be able to avoid a collision, but may be capable of reducing the impact speed to 40 km/h or below. This would bring such a collision into the scope of benefits of other safety measures such as VRU impact protection.

Although VRU impact protection and pedestrian AEB address the same target population, it is also clear that they can be arranged to complement each other and could work together to protect a greater range of VRUs than would be possible for either in isolation. This is a result of low AEB effectiveness for impacts at the outer edges of the vehicle and the fact that a significant proportion of HGV to VRU collisions occur at speeds in excess of 40 km/h, which is typically beyond the capability of impact protection. However, working together, AEB could reduce impact speeds to less than 40 km/h, which is within the scope of VRU impact protection, such that a significant proportion of fatalities could be prevented by combining the measures.

At this moment in time, few commercial vehicle manufacturers fit AEB systems that are effective in pedestrian or cyclist crossing scenarios. Mercedes were first to market with their Active Brake Assist 4 (Annex 3.13), which upgrades their AEB system to enable the detection of VRUs. Alexander Dennis has also announced plans to implement pedestrian AEB on a city bus for the first time in 2018. For both examples, no details of technical performance have yet been made fully public.

8.1.2 Close proximity manoeuvres

When considering the HGV manoeuvres associated with close proximity VRU collisions, it is clear that a substantial number of VRUs are injured when they are in close proximity to HGVs that are turning to the nearside and when HGVs pull away from rest. Importantly, it is mainly, but not exclusively, cyclists that are injured by the former mechanism and mainly, but also not exclusively, pedestrians by the latter (Annex 1.3.3.2).

Robinson *et al.*, (2016) showed that elderly pedestrians were disproportionately at risk in collisions involving HGVs pulling away from rest and in-depth studies uniformly showed that visibility through the windscreen was a key issue when the driver pulled away. Blind spots have been closely associated with cyclists killed by turning HGVs (Robinson *et al.*, 2016). In these cases, the cyclist stayed in the region of the front-nearside of the HGV cab for the entirety of the manoeuvre, which is an area known to suffer from blind spots in many HGVs. However, in the remaining collisions the cyclist was often positioned much further to the rear of the cab at the precise moment in the manoeuvre when the driver would need to see the VRU in order to react, brake and avoid these collisions. In most of these cases, the cyclist should have been visible in the HGV mirrors at that time.

For some time now, aftermarket systems have been available that act as VRU proximity warnings (Cook *et al.*, 2011b). These short-range sensors trigger any time a VRU enters a set distance of the HGV to warn the driver. The quality of these devices can therefore vary widely, particularly in terms of ‘false positives’ (low or zero risk situations where a warning is still issued). False positives have been reported to erode driver confidence in the warning systems and lead to warnings being either ignored or disabled, with systems that avoided excessive false positives significantly reducing the reaction times for drivers. As such, AEB systems could have potential benefits for mitigating the outcomes for low-speed turning or moving off collisions.

When considering moving away from rest collisions, there is significant overlap between the direct and indirect vision safety measures and primary active safety systems based on sensor-based VRU detection systems. Indirect vision devices render the image of the pedestrian at much smaller than life size, often in an unnatural position to look at (e.g. top corner of windscreen) and sometimes with image distortion. These devices also rely heavily on the driver looking in the right place at the right time. Sensor based warning systems can overcome these limitations by attracting the drivers attention in the correct direction; however, they rely on the driver recognising the meaning of the warning and reacting appropriately. Direct vision improvements will not suffer the limitations of these indirect vision devices; however, such improvements will incur significantly greater costs.

The situation is different for turning collisions, where a much smaller proportion of the target population of casualties can be prevented by improving direct vision performance. Many of these casualties are, at the critical moment, already visible in mirrors, but this vision is clearly insufficient to prevent the collision (for example because the driver is not looking in the right mirror at the right time). Effective primary active safety systems, that automatically brake during turning manoeuvres, therefore carries significant potential for further enhancing the safety of HGVs during turning manoeuvres.

Although the authors are not aware of such systems yet being implemented on any new HGV, a tier one supplier Wabco is now promoting its OnCity system (WABCO, 2016). This is a LIDAR based system that Wabco claims can monitor all along the blind side of the HGV, that can detect imminent collisions with VRUs while turning and automatically apply the brakes to avoid collision. Such a system, if effective, has the potential to eliminate most, if not all, of the target population for direct and indirect vision in turning collisions. As such, there is a strong overlap with the TFED measures in relation to turning.

8.2 Car Occupants

Car occupants are the group most commonly killed in collisions involving HGVs and the biggest single group is in head on collisions. This is the group targeted by enhanced front underrun protection (see Section 6). Most of the collisions of this type involve one of the two vehicles crossing the central white line on a two lane undivided highway with one lane in each direction. Thus, active safety systems intended to keep vehicles in their lane have the potential to influence this particular target population.

Lane departure warning (LDW) has been mandatory on new HGVs since 2015. It was not thought to be a common fitment before that date, so vehicles equipped with LDW will still represent a relatively small proportion of the HGV fleet. It is not mandatory on passenger cars, however, but has been a relatively popular voluntary fitment for some years. Thus, if it proves effective in service, a reduction in car occupant casualties would be expected from the increased market penetration of this existing technology in both HGVs and cars. Post-hoc research regarding the effectiveness of LDW on passenger cars has, however, been somewhat ambiguous, with initial studies finding that LDW actually increased claims in two vehicles studied (IIHS, 2012). The authors are not aware of any study examining the observed effectiveness of the mandatory introduction of LDW on HGVs.

Analysis of Insurance Institute for Highways Safety (IIHS) information on passenger car insurance claims in the USA found that forward collision warning systems was effective, but only about half as effective as the systems that also had autonomous braking (IIHS, 2014). If the same mechanisms hold true for lane departure collisions, then it would be reasonable to expect that a lane keeping assist (LKA) system, which intervenes to keep the driver in the lane, would be more effective than a LDW system. An emergency lane keep assist system can combine a lane keeping system, with monitoring of the traffic situation via forward AEB sensors. If a centreline is crossed when there is no oncoming vehicle, then a lesser response is issued (perhaps a visual or tactile warning). However, if this manoeuvre is undertaken when the sensors detect an oncoming vehicle, the ESC system can be used manoeuvre the vehicle out of the collision path.

Emergency lane keep assist systems are already available on some high end passenger cars (e.g. Mercedes) and are due to become a Euro NCAP requirement in future. It is, however, not yet available for HGVs and technical differences in steering may make it more challenging to implement. In head-on collisions between HGVs and cars, however, a significant proportion of collisions will be cause by cars that have moved out of their lanes. Thus, there is more potential for lane keep assist systems fitted to cars to compete with the safety measures investigated by this project, than there is for lane keep assist systems fitted to HGVs.

8.3 HGV Occupants

Volvo Trucks (2013) found that 20% of killed or seriously injured HGV occupants were in a collision with the rear of another HGV and a further 10% were involved in head-on collisions with HGVs. AEBS was made mandatory in 2015 in order to avoid or mitigate the consequences of front-to-rear collisions. The minimum requirements of the regulation are relatively modest, such that the system must reduce collision speeds with stationary vehicles ahead by at least 10 km/h (to be increased to 20 km/h in 2018) from an initial speed of 80 km/h. The 2018 standard can already be greatly exceeded by most vehicles with Volvo, for example, claiming complete avoidance (in test conditions) of a stationary vehicle from a speed of 80 km/h and at a speed of the maximum 90 km/h a reduction in impact speed to around 10 km/h (Knight and Avery, 2015).

These achievements will not be replicated in all conditions, for example, performance can be less or even non-existent in poor lighting conditions, poor weather or where the road curvature restricts narrow beam radar line of sight. Thus, this active safety measure will not completely eliminate the type of collision where improved crashworthiness would be expected to benefit truck occupants. However, it is a recent measure with low voluntary fitment before 2015, so penetration of the vehicle fleet is likely to be relatively low. Thus, any increase in the HGV fleet penetration would be expected to substantially reduce the population of HGV occupant casualties that collide with the rear of another vehicle.

9 Clustering of Safety Measures

9.1 Introduction

The European Commission (EC) wish to regulate a number of safety measures as part of the cab length derogations provided by Directive (EU) 2015/719. When implementing a cluster of regulated safety measures as part of such a policy, the EC must consider which clusters provide the most cost-effective option to the EU. When considering clustering the five safety measures reviewed by this project, it was evident that there were overlaps in the target populations addressed by the individual measures and that there was also the potential to share critical components between safety measures. Following the general clustering method presented in Section 2.5, the following sections provide further detail on the methods used to evaluate the cost-effectiveness of the clusters and the outcomes of this evaluation.

9.2 Clustering Approach

9.2.1 Selection of safety measure solutions

Of the five safety measures investigated within this project, three evaluated the cost-effectiveness of multiple approaches. The selection of the most cost-effective approach for the clustering analysis was, however, critical to ensuring each safety measure cluster was assessed based on their most cost-effective solutions. For this reason, the below list of safety measures were selected for the clustering process, as they were the most cost-effective approach for each safety measure investigated in Sections 3-7:

- Direct Vision [DIR]
  - Best-in-class direct vision approach based on the performance of a Low Entry Cab
- Indirect Vision [IDV]
  - Best-in-class 360° field of view passive camera [CAM] system
  - Best-in-class blind-spot VRU detection [DET] system
- Vulnerable Road User Impact Protection [VIP]
  - Best-in-class 1.0 m tapered front-end extension
- Front Underrun Protection [FUP]
  - Best-in-Class 0.8 m front end extension
- Vulnerable road User Airbag [VAB]
  - Best-in-class front-nearside and front-offside airbags
- Combined VIP and FUP Front End
  - Mid-range 0.5 m VIP and mid-range 0.4 m FUP front-end extensions

9.2.2 Clustered casualty reduction benefits

To estimate the casualty reduction benefits for a safety measure cluster, the interactions of each safety measure on the target populations that remain for other safety measures were accounted for. These were prioritised by the order that the safety measure would intervene during each collision phase. These were organised into 'layers', as described in Section 2.5, whilst further prioritisation was performed for the safety measures within each layer. The use of prioritised safety measures ensured that the combined effects of all preceding safety measures were accounted for prior to calculating the casualty reduction benefits from the remaining target population.

The casualty reduction benefit for each safety measure cluster was calculated from the number of casualties prevented by each consecutive safety measure implemented by the cluster. This was evaluated by determining an initial target population for the highest priority safety measure and calculating the casualty reduction benefits using the overall effectiveness of the safety measure. These prevented casualties are then removed from the remaining target population for the second highest priority safety measure within the cluster, before also calculating the casualty reduction benefits for this safety measure. This process was repeated until the effects of all safety measures within the cluster had been assessed. The clustering priorities for the safety measures evaluated by this project are shown below in Figure 14:

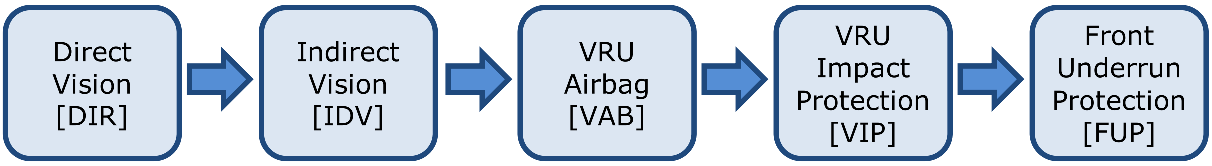


Figure 14: Priority levels for clustering methodology

This approach was performed for each target population (pedestrians, pedal cyclists and car occupants) and each injury level for each safety measure cluster. Casualty reductions and, consequently, the casualty reduction benefits were subsequently calculated for each cluster using the calculations specified in Section 2.6. It should be noted that the benefits for clusters which include the VRU impact protection and front underrun protection safety measures used best-in-class performance levels, aside from when both safety measures were included in the same cluster, where the mid-range values were used instead.

9.2.3 Clustered costs

To estimate the clustered costs for a safety measure cluster, the potential for sharing the costs of critical components between the clustered safety measures was assessed. Two cost clusters were identified from the five key safety measures. The first cost cluster was identified as the costs associated with the redesign of the enhanced truck front end, with these costs shared between the direct vision, VRU impact protection and front underrun protection safety measures when clustered. The second cost cluster was identified as the costs associated with the sharing of camera sensor systems between the two approaches adopted by the indirect vision safety measure (camera and detection systems).

When clustering costs, the proportion of fixed costs to the variable costs is the key factor for determining the value of costs that may be saved. The fixed costs relate to the costs that will always be incurred by the safety measure through the manufacture, installation and certification of the device regardless of clustering, whilst the variable costs relate to the costs that are shared between the clustered safety measures through the mutual use of parts and other shared costs. Due to a paucity of evidence surrounding the breakdown of the costs for each safety measure into fixed and variable costs, it was approximated that each safety measure the costs would be made up of 50% fixed costs and 50% variable costs. This would mean that the combination of two safety measures in a cluster would result in clustered costs of only 75% the total costs of the two measures, whilst the combination of three safety measures in a cluster would result in costs of only 66% the total costs of the measures in the cluster.

9.2.4 Clustering and ranking

With five safety measures, and the indirect vision safety measure having two separate approaches, a total of 63 different safety measure clustering combinations were possible. Ranges for the costs per vehicle, total fleet costs, casualty reduction benefits, monetised casualty benefits, break-even costs and benefit-cost ratios were then calculated for each safety measure cluster using the previously described clustering strategies. Benefit-cost ratios were, again, calculated over a 10-year assessment period.

To assist with identifying the most cost-effective safety measure clusters, the outcomes were then ranked through a least risk approach. This involved the ranking of each safety measure cluster based on the lower boundary of its benefit-cost ratio range. The top ten ranked clusters were then selected as the most cost-effective solutions.

9.3 Outcomes

9.3.1 Uniform approach

The top ten ranked safety measure clusters when using the uniform approach are shown below in Table 31. Of the top ten ranked safety measure clusters, the sensor-based detection system and front underrun protection system safety measures were found to feature heavily. The highest ranked cluster was found to be the sensor-based detection systems safety measure. This was closely followed by the combination of the detection system and front underrun protection system safety measures and the front underrun protection system safety measure on its own. Although both of these safety measures are ranked lower than the detection system safety measure on its own, they both have considerably higher cost-effectiveness potential due to having greater benefit-cost ratio ranges, whilst also preventing a considerably larger proportion of KSIs. Of the remaining cost-effective clusters the VRU impact protection, direct vision and VRU airbag safety measures also featured in a number of clusters.

Table 31: Top ten ranked safety measure clusters for the uniform approach

Rank	DIR	CAM	DET	VIP	FUP	VAB	Benefit-Cost Ratio	KSI Reduction
1			✓				**1.40-2.47**	201-322
2			✓		✓		**1.25-3.62**	939-1964
3					✓		**1.16-4.39**	738-1643
4				✓			**1.10-2.37**	497-756
5			✓	✓			**1.09-2.19**	658-989
6	✓				✓		**1.04-3.32**	982-2282
7			✓	✓	✓		**1.04-2.75**	1072-2230
8			✓		✓	✓	**1.00-3.03**	1088-2315
9	✓		✓		✓		*0.99-2.75*	1096-2381
10	✓			✓			*0.99-2.19*	680-1200

9.3.2 Differentiated approach

The top ten ranked safety measure clusters when using the differentiated approach are shown below in Table 32. Of the top ten ranked safety measure clusters, sensor-based detection and front underrun protection systems were again found to feature heavily. The highest ranked safety measure cluster was the front underrun protection system, with this being the only cluster found to be cost-effective for the differentiated approach.

Table 32: Top ten ranked safety measure clusters for the differentiated approach

Rank	DIR	CAM	DET	VIP	FUP	VAB	Benefit-Cost Ratio	KSI Reduction
1					✓		**1.01-3.85**	372-828
2			✓		✓		*0.91-2.83*	432-924
3	✓				✓		*0.75-2.47*	445-1019
4			✓				*0.73-1.29*	60-97
5					✓	✓	*0.68-2.63*	420-908
6			✓		✓	✓	*0.68-2.22*	477-995
7	✓		✓		✓		*0.67-2.00*	479-1049
8				✓	✓		*0.66-2.15*	389-888
9			✓	✓	✓		*0.65-1.88*	451-1041
10		✓	✓		✓		*0.61-2.25*	457-1026

10 Conclusions

This project is the first to evaluate the cost-effectiveness of a range of clustered safety measures for improving vulnerable road user (VRU) and car occupant protection via the HGV cab length derogations proposed in Directive (EU) 2015/719. These safety measures were defined by the European Commission (EC) and concerned regulating improvements to the direct vision, indirect vision (including both cameras and detection systems), VRU impact protection, front underrun protection and VRU airbag performance of HGVs with enhanced truck front end designs (TFEDs).

The project performed a state-of-the-art review of exemplar and conceptual technologies relevant to HGVs with enhanced TFEDs. This was followed by a systematic review and critical appraisal of the literature to establish relevant target populations, effectiveness values and costs associated with each safety measure. The effects of clustering both the casualty reducing benefits and production related costs were then calculated for a total of 63 safety measure clusters, with the benefit-cost ratios of each individual safety measure and safety measure cluster ranked in order of cost-effectiveness. This was performed for two different approaches based on two separate fleet penetration models for enhanced TFEDs. These were the "uniform" approach, which assumed equal uptake across all HGV applications and vehicle types, and the "differentiated" approach, which assumed that articulated HGVs in long haulage operations would be the only sector to adopt cab length derogations. Finally, the potential regulatory options available for each individual safety measure were considered alongside the potential benefits and limitations of each option.

The benefit-cost ratios of all individual and clustered safety measures associated with the differentiated approach were found to be considerably lower than their equivalent values for the uniform approach. When considering the uniform approach, three individual safety measures were observed to be cost-effective (benefit-cost ratio ranges of >1), whilst a further five safety measure clusters were found to be cost-effective (Table 33). When considering the differentiated approach, however, only a single safety measure, for FUP, was found to be cost-effective. For the uniform approach, the highest ranked cluster was observed to be the sensor-based detection system safety measure on its own. This was followed up by a combination of the detection system and FUP safety measures and the FUP safety measure on its own.

Table 33: Top ten ranked safety measure clusters for the uniform approach

Rank	DIR	CAM	DET	VIP	FUP	VAB	Benefit-Cost Ratio	KSI Reduction
1			✓				**1.40-2.47**	201-322
2			✓		✓		**1.25-3.62**	939-1964
3					✓		**1.16-4.39**	738-1643
4				✓			**1.10-2.37**	497-756
5			✓	✓			**1.09-2.19**	658-989
6	✓				✓		**1.04-3.32**	982-2282
7			✓	✓	✓		**1.04-2.75**	1072-2230
8			✓		✓	✓	**1.00-3.03**	1088-2315
9	✓		✓		✓		*0.99-2.75*	1096-2381
10	✓			✓			*0.99-2.19*	680-1200

Despite these significant outcomes, there were several limitations that could potentially affect the applicability and generalisability of these results. Firstly, although this project used, as best it could, an evidence base established on the current state-of-the-art in the research literature, a number of assumptions were made due to the paucity of relevant information. Key assumptions involved simplifying the benefit-cost analysis to discount the temporal trends associated with the HGV fleet, collision landscape and costs over the 10-year analysis period, the simplification of CARE database uplift factors, the mapping of target populations between the safety measures in the same cluster, the exclusion of slight injuries from the analysis and the assumption that all casualties are avoided rather than mitigated. Further assumptions were made when estimating overall effectiveness values for each safety measure, particularly when considering the correction factors, and the assumptions made regarding the proportion of articulated HGVs in the total EU HGV parc and involved in collisions with each target population.

To further understand the effects of these assumptions, a sensitivity analysis could be performed (this was out of scope for the project). Should this analysis be performed, two key parameters that have high levels of uncertainty should be prioritised for investigate further. These include the cost values used for the safety measures, where a stakeholder consultation would be of benefit, and the assumption that all casualties were prevented, rather than mitigated, by each safety measure.

This project further identified the regulatory options available to all safety measures. For each safety measure, all regulatory and standardised testing and assessment protocols underpinning each safety measure were considered to understand the changes needed to ensure the relevance of future regulatory requirements to HGVs with enhanced TFEDs. These concluded that the indirect vision and front underrun protection safety measures would require an update of existing regulations, whilst the remaining measures would require the development of new regulations adapted from the protocols proposed by the HGV Direct Vision Standard (DVS) and Heavy Vehicles Aggressivity Index (HVAI).

Finally, the areas where further research should be performed to confirm the values used in this project were also identified. As a large proportion of effectiveness values were not based upon empirical evidence specific to the differences in performances between HGVs with regulated and unregulated TFEDs, the overall effectiveness values used within this project will require further confirmation. The costs used in this project were similarly affected, with further confirmation required for the cost ranges of each individual and clustered safety measure via industry stakeholder consultation. The target populations used by this project were less affected, but further research should be performed to better evaluate the differences in outcome associated with the differentiated approach.

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Annex 1 Review of Target Populations, Effectiveness and Costs

Annex 1.1 Introduction

This project systematically identified, interpreted and appraised all research relevant to establishing the target populations, effectiveness and costs associated with traditional and enhanced truck front end designs (TFEDs). A standardised framework was utilised to identify and assess the quality of pertinent information sources in order to extract relevant data in an unbiased and replicable manner.

This Annex will therefore describe the processes of source selection, critical appraisal and data analysis employed to extract relevant data from the selected articles. The Annex will further describe the conclusions of this systematic review to identify the target populations, effectiveness and costs for each safety measure.

Annex 1.2 Methods

This systematic literature review was conducted following the core principles and methods described by Seidl *et al.* (2017). Following these predefined processes, this literature review was completed in the four key steps outlined below in Figure 15.

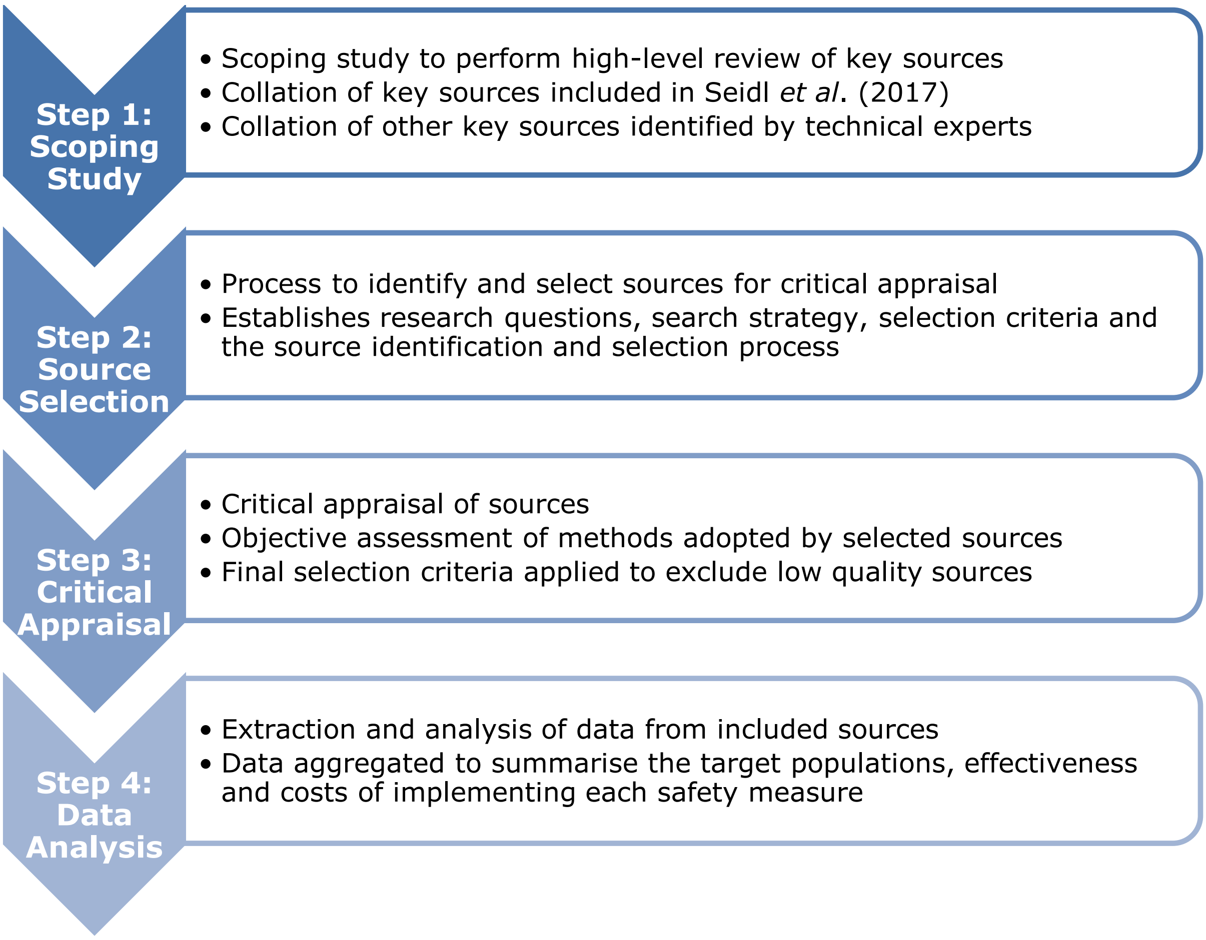


Figure 15: Top-level overview of systematic literature review process

Annex 1.2.1 Scoping Study

This scoping study identified studies that were collated during previous research (Hynd *et al.*, 2015;Seidl *et al.*, 2017) and that were deemed relevant to the safety measures in the scope of this project (see Section 2.3 for greater detail on safety measures). These sources were further supplemented by several other key sources that were identified by technical experts.

Sources were selected for critical appraisal if they met one of the following inclusion criteria:

- The source contained quantitative primary data on the positive and negative impacts of safety measure implementation (e.g. casualty benefits, costs, etc.)
- The source contained evidence that could be used to indirectly calculate the positive and negative impacts of safety measure implementation (e.g. reduction in reaction times by improved direct vision, reduction in injury risks due to improved pedestrian crashworthiness structures, etc.)
- The sources contained evidence that could be used to assess the potential maximum target population relevant to each safety measure

In addition to being selected for critical appraisal, the bibliographies of these sources were queried to identify any further studies cited by these sources that were deemed relevant to the safety measures investigated in the scope of this project. Finally, all sources identified during this scoping study were used to establish the inputs for the source selection process.

Annex 1.2.2 Source Selection

The source selection process adopted a standardised approach for systematically searching for, and selecting, the sources relevant to the investigated safety measures. This approach, performed by the TRL Library and Information Centre on 31st March 2017, required the development of five key research questions to establish a search strategy for several literature databases. This search strategy was implemented, in combination with predefined selection criteria, to identify and select sources for critical appraisal. The following sections summarise the approaches taken for each of these steps.

Annex 1.2.2.1 Research questions

For each safety measure investigated by this project, a number of research questions were designed to query literature databases for the purposes of locating and identifying relevant research. These questions used the TIO (Target Group [T], Intervention [I] and Outcome [O]) approach to structure and formulate each research question.

- *What effect does direct vision performance [I] have on the frequency and severity [O] of HGV collisions with vulnerable road users and light vehicle occupants [T]?*
- *What effect do indirect vision systems [I] have on the frequency and severity [O] of HGV collisions with vulnerable road users and light vehicle occupants [T]?*
- *What effect does HGV frontal impact compatibility [I] have on the frequency and severity [O] of HGV collisions with vulnerable road users and light vehicle occupants [T]?*
- *What effect does frontal underrun protection [I] have on the frequency and severity [O] of HGV collisions with vulnerable road users and light vehicle occupants [T]?*
- *What effect do vulnerable road user airbags [I] have on the frequency and severity [O] of HGV collisions with vulnerable road users and light vehicle occupants [T]?*

Annex 1.2.2.2 Search strategy

A list of appropriate keywords, focussed around the requirements of the research questions, was then generated for each TIO search term. These keywords are shown below in Table 34 for the Target Groups [T], Table 35 for the Interventions [I] and Box 1 for the Outcomes [O].

Once a full list of keywords for the Target Group, Interventions and Outcome were finalised, these were transferred into a query with the following logical structure:

(“A” or “B” or “C” or…) AND (“D” or “E” or “F” or…) AND (“G” or “H” or “I” or…)

Where A, B, C are the Target Group keywords; D, E, F are the Interventions keywords, and G, H, I are the Outcome keywords. Boolean logic operators (OR/AND) were also used to limit the scope of the search.

Table 34: Target group [T] keyword options for search strategy

VRU[†]	Car[†]	HGV	Collision
VRU Vulnerable Road User Pedestrian Cycl* Bicycl* Bike	Car Passenger Occupant Driver Van Light vehicle M1 N1	HGV Truck Heavy Goods Vehicle Lorr* Articulated N2 N3 Aerodynamic cab Extended cab Front end design	Collision Accident Crash Impact Run over Under run

*Wildcard term; [†] VRU and car investigated separately for each safety measure.

Table 35: Intervention [I] keyword options for search strategy

Direct Vision	Indirect Vision	Frontal Impact Compatibility	Front Underrun Protection	VRU Airbag
Direct vision Visibility Visible Low Entry Cab Door window Blind spot	Indirect vision Sensors Camera Proximity Detect* Warning Alert Monitoring Obstacle detection	Frontal Small overlap Offset Full width Full overlap Head on Compatibility Crashworth*	Front Underrun Protect* FUPD FUP Run-over protect* Front under-ride protect*	Cycl* Airbag Pedestrian Airbag Vulnerable Road User Airbag

*Wildcard term.

Box 1: Outcome [O] keywords list for search strategy

Outcome
Frequen*, Sever*, Rate, Incidence, Prevalence, Trauma, Injury, Casualty, Hospital, Mortality, Morbid*, Fatal*, Killed, KSI, Slight*, Serious*, Abbreviated Injury Scale, AIS, Incapacity, Disability

*Wildcard term.

Table 36 illustrates how these keywords were implemented for a particular search strategy. Three target groups were used in this case to control for the requirement to search for HGV collisions with vulnerable road users.

Table 36: Example search strategy for searching for literature relevant to the effects of direct vision performance on vulnerable road user collisions with HGVs

Target Group 1 [T_1]	Target Group 2 [T_2]	Target Group 3 [T_3]	Intervention [I]	Outcome [O]
VRU	HGV	Collision	Direct Vision	Frequen* Sever*
Vulnerable Road User Pedestrian Cycl* Bicycl* Bike	Truck Heavy Goods Vehicle Lorr* Articulated N2 N3 Aerodynamic cab Extended cab Truck front end design	Accident Crash Impact Run over Under run	Visibility Visible Low Entry Cab Door window Blind spot	Rate Incidence Prevalence Trauma Injury Casualty Hospital Mortality Morbid* Fatal* Killed KSI Slight* Serious* Abbreviated Injury Scale AIS Incapacity Disability

*Wildcard term.

Annex 1.2.2.3 Literature databases

All online databases available to the TRL Library and Information Centre, which provides an archiving and records management service for TRL, were searched for relevant sources. The databases searched on behalf of this literature review are outlined overleaf.

TRID (Transport Research International Documentation): TRID is a database that combines ITRD (OECD's International Transport Research Documentation database) and the US-based database TRIS (Transport Research Information Service). Together they form one of the most comprehensive transport research databases available today.

http://trid.trb.org/

ScienceDirect: ScienceDirect is a leading full-text scientific database offering journal articles and book chapters from more than 2,500 peer-reviewed journals and over 11,000 books.

http://www.sciencedirect.com/

ITRP Transport Research Portal: ITRP is portal for accessing information from databases of past and ongoing research projects worldwide. This portal is an international collaborative project funded by the European Commission FP7 programme. Its aim is to foster closer and more effective communication between researchers working in the field of transport technologies, both in the EU and internationally. It seeks to do this by facilitating exchange of information and developing a framework for long term collaboration.

http://www.intransport.eu/search/index.php

ARRB Knowledge Base: The ARRB knowledge base a free full text searchable resource of ARRB publications from 1962 to present, including conference papers, reports and bulletins. There are over 5,000 items in the resource with more being added as they are scanned.

http://arrbknowledge.com

PubMed: PubMed Is a public version of MEDLINE, arguably the world's largest medical database. Its records contain many levels of medical research from meta-analyses and systematic reviews to case studies. It includes accident studies, safety, human factors, psychology etc.

http://www.ncbi.nlm.nih.gov/pubmed/

TRIP (formerly the Transport Research Knowledge Centre): TRIP gives you an overview of in-progress and completed transport research activities at European and national levels, based around the EU research framework funding programme.

http://www.transport-research.info/web/index.cfm

Google Scholar: Google Scholar is a freely accessible web search engine that indexes the full text or metadata of scholarly literature across an array of publishing formats and disciplines. Released in beta in November 2004, the Google Scholar index includes most peer-reviewed online journals of Europe and America's largest scholarly publishers, plus scholarly books and other non-peer reviewed journals.

http://scholar.google.co.uk/

Annex 1.2.2.4 Source selection criteria

This search first excluded all English language sources published before the 1st January 2010, based on a hypothesis that all relevant sources published prior to this date would have been identified by the scoping study. All duplicate sources, conference abstracts, editorial letters, review articles and statements of expert opinion were excluded. Source titles and abstracts were then screened for relevance based upon the criteria previously specified in Annex 1.2.1, with identified sources included for the detailed review of the full manuscript. Finally, the bibliographies of all the sources that were selected for full text review were recursively searched for further relevant sources.

Annex 1.2.3 Critical appraisal

To ensure only high quality sources were selected for inclusion, the source assessment process first developed by Seidl *et al.* (2017) was adopted by this project. This allowed for an objective assessment of the relevance and methodological quality of each source, therefore contributing to the efforts of the EC to standardise and improve the quality of assessments.

The source assessment process developed by Seidl *et al.* (2017) grades the selected sources such that an objective judgement can be made as to whether the quality of data is sufficient to be included in the review. Each source was appraised and graded against standardised criteria for the parameters described in Figure 16 overleaf (a full description of these standardised criteria is provided in Annex 1 of Seidl *et al.* (2017)).

Reviewers were trained in applying the process and the consistency of reviews was assured via a system of spot checks and individual feedback. Each of these parameters was assessed and assigned a standardised score determined based on the reviewer's assessment of the source against each of these criteria. Scores were combined to provide a rating score that ranged between 0-100%, with 100% denoting the highest possible quality rating a source could achieve. A minimum rating score of 50% was adopted as the methodological quality exclusion criteria, with sources failing to achieve this excluded from the literature review.

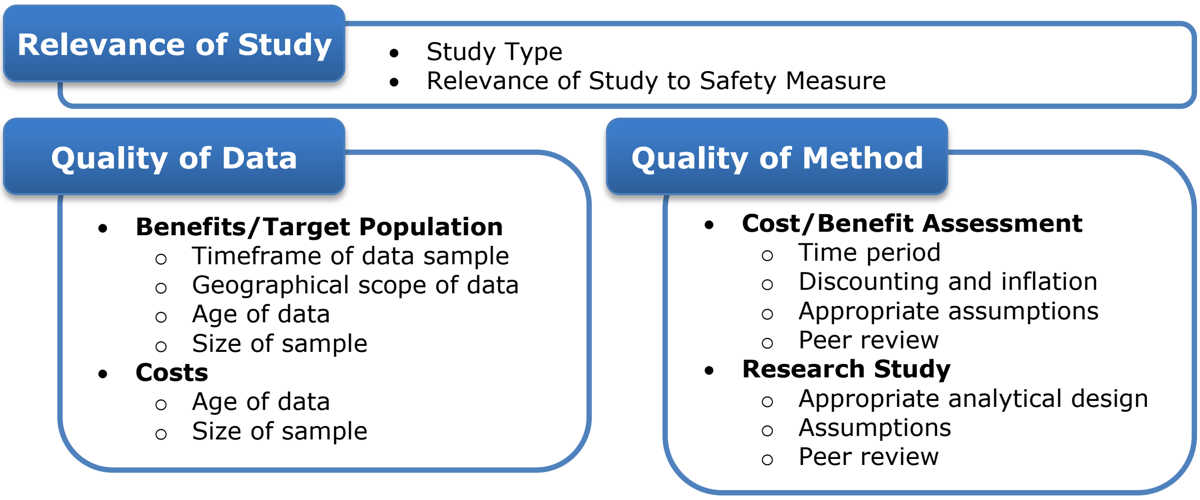


Figure 16: Standardised criteria used for assessing and grading sources during the source assessment process (Seidl *et al.*, 2017)

Annex 1.2.4 Included sources

The flow of sources through the source selection process can be seen in the flow diagram in Figure 17. A total of 277 sources were returned from the source selection process, of which 235 were excluded based on the criteria. Of the 65 articles selected for the source assessment, a total of 52 met the selection criteria and were included for full evaluation.

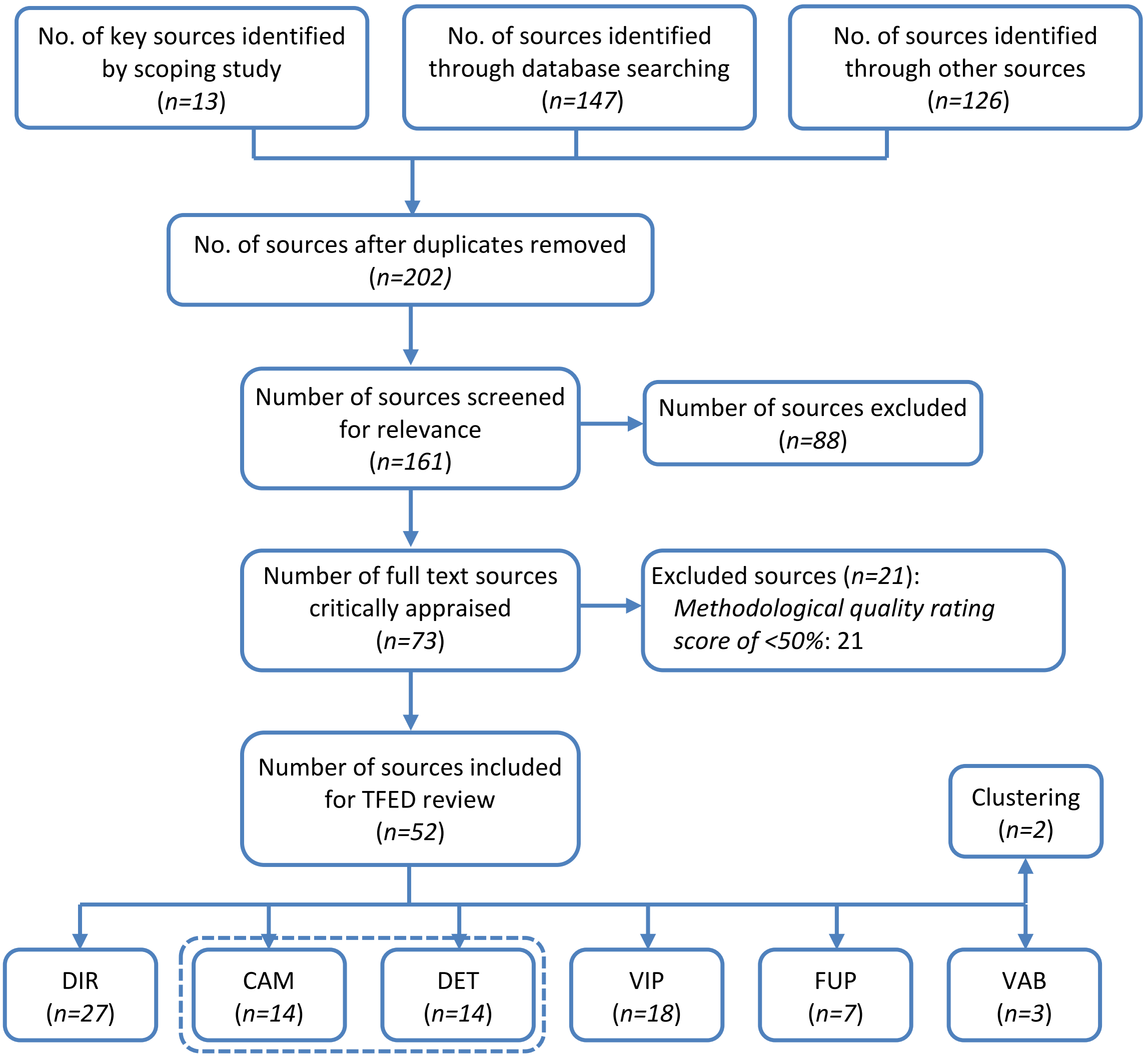


Figure 17: Source selection process flow diagram

Of the 52 included sources, 27 (52%) reported on direct vision [VIS], 15 (29%) reported on indirect vision [IDV] (14 (27%) for cameras [CAM], 14 (27%) for detection systems [DET]), 18 (35%) reported on VRU impact protection [VIP], 7 (13%) reported on front underrun protection systems [FUP], 3 (6%) reported on VRU airbags [VAB] and 2 (4%) reported on the clustering of safety measures. A total of 33 (63%) sources, however, reported on multiple safety measures without taking into consideration the effects of the clustering of target populations or technologies.

Annex 1.2.5 Data Analysis

The 52 sources included for analysis within this review included 14 (27%) sources that contained relevant information on the target population for each safety measure, 40 (77%) sources containing relevant information on safety measure effectiveness and 21 (40%) sources containing relevant information on the costs of each safety measure. The following sections therefore provide a descriptive overview of the data aggregated from all sources included within each data analysis section.

Annex 1.3 Target Population

A target population is the total number of fatalities or injured casualties that a particular safety measure intends to either prevent or mitigate. A key factor to be considered when identifying target populations includes characterising the collision scenarios for which the safety measure was originally intended. This can include the identification of causation factors, vehicle manoeuvres, opponent manoeuvres and impact configurations in addition to understanding any differences between these characteristics based on vehicle types.

The aim of this section is to therefore identify and analyse the target populations that are relevant to the technologies researched in each of the safety measures. It must be noted that, to keep the terminology consistent in this report, vehicles performing right turns in Europe and left turns in the UK, and vice versa, shall be grouped together.

Annex 1.3.1 European Overview

The Community database on Accidents on the Roads in Europe (CARE) holds high level information on collisions resulting in fatalities or injuries from European Member States. The most recent annual report states that in 2014 there were 3,863 fatalities due to collisions involving HGVs in excess of 3.5 tonnes in EU 28 countries[3]. This figure has dropped by almost 50% since 2004, but collisions involving HGVs still account for 15% of all road fatalities in the EU (Figure 18) (ERSO, 2016).

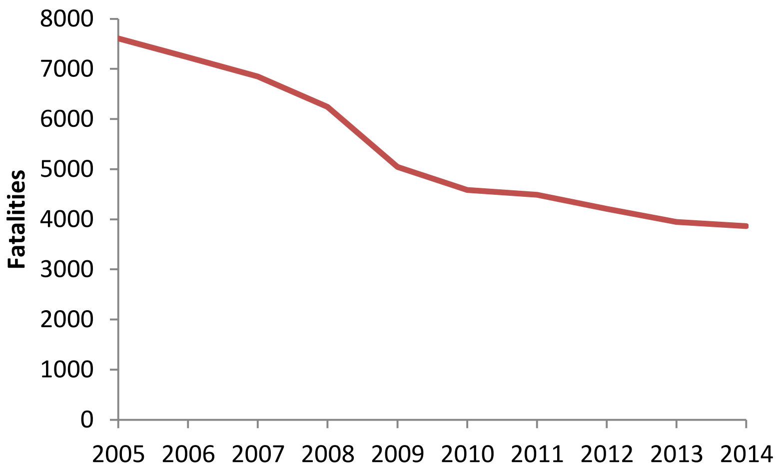


Figure 18: Number of fatalities involving HGVs in EU 28 countries. (CARE database, data available in May 2016).

[3] EU 28 countries: AT, BE, BG, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SE, SI, SK, UK.

Car occupants are the most common fatality in collisions involving HGVs accounting for almost half of such fatalities (Figure 19). Pedestrian and pedal cyclists, when considered together, are the next most common opponents in HGV collisions in terms of fatalities. A substantial proportion of HGV occupants are also killed during collisions involving HGVs.

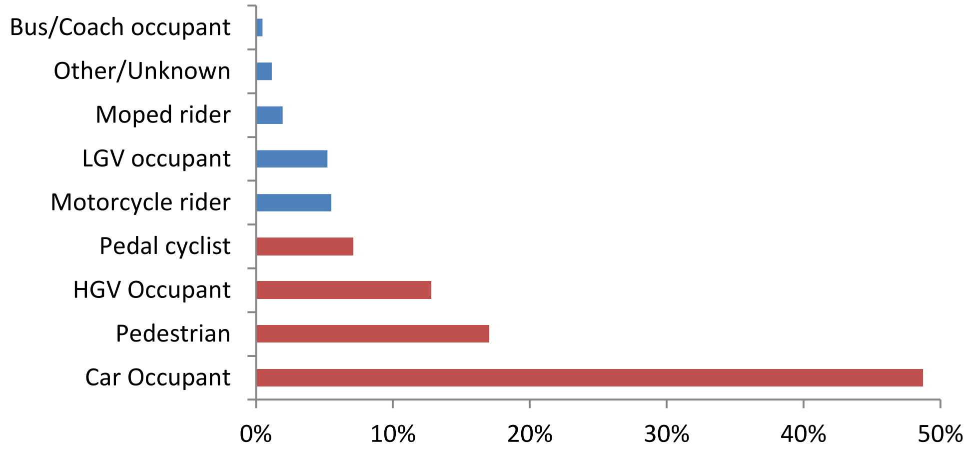


Figure 19: Distribution of fatalities due to collisions involving HGVs by road user type in the EU 28 during 2014 (or latest available year) (ERSO, 2016).

A similar trend was also observed when considering injured casualties involved in HGV collisions (Figure 20). Car occupants accounted for almost over half of injured casualties involved in HGV related collisions, with 36,717 injured casualties reported in 2015 across EU 25[4] countries. Pedal cyclists were more frequently injured than pedestrians, but there were twice as many pedestrian fatalities than cyclist fatalities in 2015.

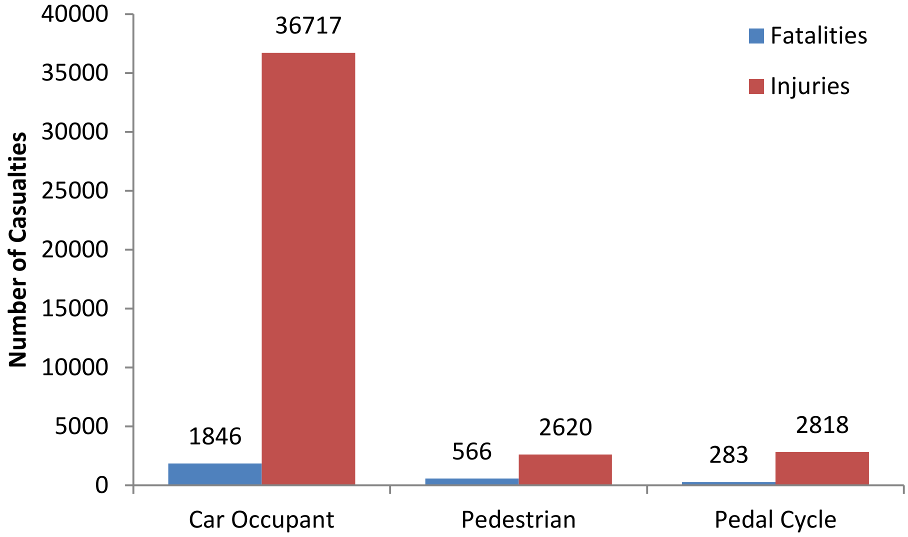


Figure 20: Number of fatalities and injuries involved in collisions with HGVs by road user type in EU 25 during 2015 (or latest available year) (CARE database, data available in April 2017).

Whilst car occupants account for the largest number of casualties involved in collisions involving HGVs, when looking at the distributions of injury severity of casualties it was apparent that pedestrians were subject to a larger proportion of more serious injuries than pedal cyclists and car occupants, whilst pedal cyclists were found to be more likely to be severely injured than car occupants (Figure 21). This unequal distribution of injury severity amongst both pedestrians and pedal cyclists has led to calls to better protect these particularly vulnerable road users (VRUs) during HGV collisions.

[4] EU 25 countries: AT, BE, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, NL, PL, PT, RO, SE, SI, SK, UK.

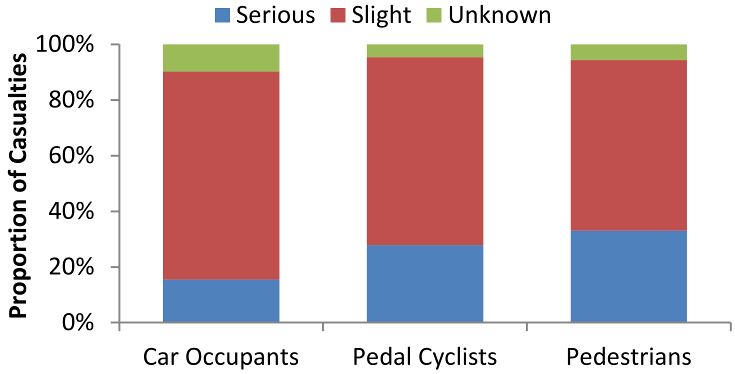


Figure 21: Proportion of all injured casualties involved in collisions with HGVs by road user type and injury severity in EU 25 during 2015 (CARE database, data available in April 2017).

As the CARE database only provides high level information of the collisions, databases at the national level and in-depth collisions studies are explored further in the following sections to obtain a more detailed breakdown of HGV collision characteristics.

Annex 1.3.2 Causation Factors

A study using Stats19 data of VRU vs HGV (7.5 tonnes and over) collisions between 2010 and 2015 showed a total of 2,443 HGV collisions involving pedestrians (*n*=1,241) and pedal cyclists (*n*=1,202) in Great Britain during this period (Summerskill *et al.*, 2017). The most common causation factors for collisions involving pedal cyclists were 'failed to look properly' and 'failed to judge other person's path or speed' (Table 37). Similarly, the most common causation factor for pedestrians was also 'failed to look properly', although this was followed by 'vehicle blind spot'.

Table 37: Distribution of causation factors assigned to collisions in Great Britain involving a HGV (≥7.5 tonnes) and pedal cyclist or pedestrian between 2010 and 2015. (Summerskill *et al.*, 2017)

Causation factor	No. of Accidents (%)	
	Pedal cyclists	Pedestrians
Failed to look properly	723 (60.1%)	284 (22.9%)
Failed to judge other person's path or speed	357 (29.7%)	50 (4.0%)
Passing too close to cyclist	321 (26.7%)	101 (8.1%)
Poor turn or manoeuvre	257 (21.4%)	105 (8.5%)
Careless, reckless or in a hurry	219 (18.2%)	80 (6.4%)
Vehicle blind spot	159 (13.2%)	125 (10.1%)

In 24 out of 27 in-depth studies of fatal collisions in London involving a HGV and cyclist, reduced driver vision was noted as a contributory factor. In six collisions the cyclist was directly in front of HGV and in 18 collisions the cyclist was positioned to the nearside of the HGV (Talbot *et al.*, 2014). In a similar study of fatal pedestrian collisions in London, the most common contributory factor assigned to collisions involving HGVs was 'vision affected by blind spot' (recorded for 12 out of 27 HGV collisions) (Knowles *et al.*, 2012).

Annex 1.3.3 Manoeuvres

Annex 1.3.3.1 Overview

A study analysing GB Stats19 data from 704 HGV collisions found that, where the 'vehicle blind spot' was registered as a contributory factor, the main manoeuvres that resulted in a fatality were pulling away (31%), followed by reversing (25%), turning to the nearside (19%) and turning to the offside (6%) (Summerskill *et al.*, 2014). VRUs were most commonly involved in collisions where the goods vehicle was either turning to the nearside, reversing or pulling away whereas motor vehicles were more frequently involved in side-wipe collisions.

HGV collisions that specifically involve a nearside turn are a recognised problem. In the Netherlands, almost 18% of all fatalities in HGV collisions are due to nearside turns; 7% of which involve pedestrians, 46% that involve cyclists and 47% that involve other road users (ETSC, 2013). Cyclists often make up the highest proportion of fatalities as a result of nearside turn collisions with a HGV and are over represented across multiple European countries (Figure 22).

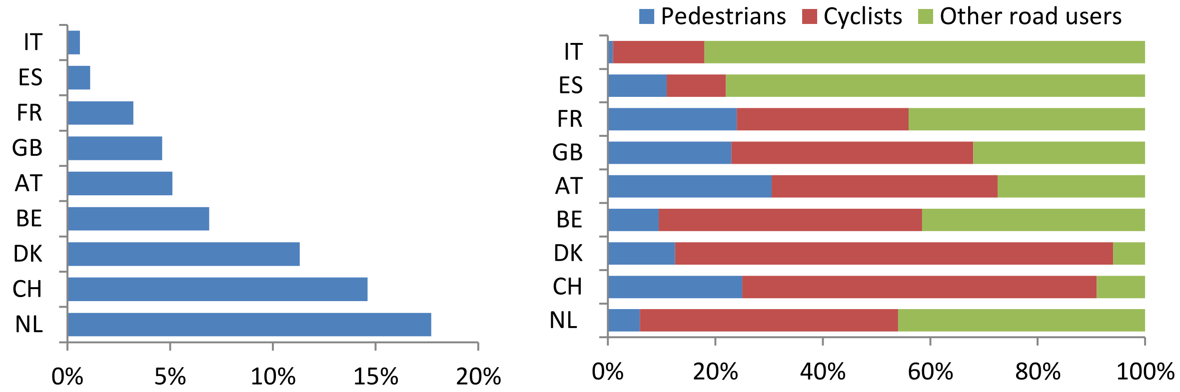


Figure 22: Percentage of road deaths in collisions involving a goods vehicle over 3.5 tonnes during 2009-2011 for which the HGV was performing a nearside turn (left) and the distribution of associated road users (right). Adapted from (ETSC, 2013).

Annex 1.3.3.2 Vulnerable road users

Data from Stats19 regarding VRU and HGV (≥7.5 tonnes) collisions between 2005 and 2014 showed that pedal cyclists are most often killed when the HGV is turning toward the nearside (72%) whereas pedestrians are most often killed as the HGV moves off (68%) (Robinson *et al.*, 2016). These observations are also seen across many other studies.

An in-depth study of 46 KSI collisions involving cyclists and HGVs of 12 tonnes or over in Germany found that the main collision scenario was found to be truck turning off to the nearside and a cyclist going straight ahead (63%) (UDV, 2016). A study of fatal pedal cyclist collisions in London found that, of the 27 collisions involving the initial contact with a HGV, over half of these collisions (16) involved the truck turning to the nearside, 9 collisions consisted of the truck and bicycle traveling alongside in the same direction and, in 2 collisions, the cyclist had priority at a junction (Talbot *et al.*, 2014).

A further study of fatal pedestrian collisions in London found that, of the 197 collisions investigated, 27 involved a HGV as the vehicle that struck the pedestrian. 15 of the 27 HGVs moving off when they struck the pedestrian, 10 were going ahead, one was turning left and one was waiting to turn/go ahead (Knowles *et al.*, 2012).

A summary of the distribution of HGV manoeuvres in pedestrian and pedal cyclist collisions involving HGVs may be seen overleaf in Table 39. When focussing on the movement of the pedestrian just prior to a collision with a HGV, however, almost a third of pedestrians were found to be crossing from the nearside, although there were a high proportion of unknown pedestrian movements (Table 38).

Table 38: Pedestrian manoeuvre prior to the HGV collision (Cook *et al.*, 2011a)

Manoeuvre	Collision Distribution	
	n	%
Crossing from nearside	35	32.1%
Crossing from offside	14	12.8%
In carriageway	12	11.0%
Walking along carriageway	4	3.7%
Unknown	44	40.4%

Table 39: Collision distribution of pedestrian and pedal cyclist collisions involving HGVs by HGV manoeuvre type

HGV manoeuvre	Injured Party	Injury Severity	No. of Collisions		Database	Source
			n	%		
Moving Off	Pedestrian	Fatals	15	55.6%	Fatal police collision files for London 2006 - 2010	Knowles *et al.*, (2012)*
	Pedestrian	Fatals	8.8	18.4%	Annual average from Stats19 2005-2014	Robinson *et al.*, (2016)
	Pedestrian & pedal cyclist	All	11	4.0%-8.0%	Stats19 2008 where 'vision affected by blind spot' was a contributory factor	Summerskill *et al.*, (2014)
	Cyclist	Fatals	3	9.1%	Annual average from Stats19 2005-2014	Robinson *et al.*, (2016)
Turning to the nearside	Pedestrian	Fatals	2.9	6.1%	Annual average from Stats19 2005-2014	Robinson *et al.*, (2016)
	Pedestrian	Fatals	2	7.4%	Fatal police collision files for London 2006 - 2010	Knowles *et al.* (2012)*
	Pedestrian & pedal cyclist	All	36	13.0-26.0%	Stats19 2008 where 'vision affected by blind spot' was a contributory factor	Summerskill *et al.*, (2014)
	Cyclist	Fatals	16	59.3%	Fatal police collision files for London 2007 - 2011	Talbot *et al.*, (2014)*
	Cyclist	Fatals	12.6	38.2%	Annual average from Stats19 2005-2014	Robinson *et al.*, (2016)
	Cyclist	All	44	33.8%	GIDAS 2008-2012	Schreck and Seiniger (2014)
Turning to the offside	Pedestrian	Fatals	1.3	2.7%	Annual average from Stats19 2005-2014	Robinson *et al.*, (2016)
	Pedestrian & pedal cyclist	All	0 -35	0.0-12.0%	Stats19 2008 where 'vision affected by blind spot' was a contributory factor	Summerskill *et al.*, (2014)
	Cyclist	Fatals	2	6.1%	Annual average from Stats19 2005-2014	Robinson *et al.*, (2016)
Side swipe to the nearside	Pedestrian & pedal cyclist	All	5	2.0-4.0%	Stats19 2008 where 'vision affected by blind spot' was a contributory factor	Summerskill *et al.*, (2014)
Side swipe to the offside	Pedestrian & pedal cyclist	All	2	1.0-2.0%	Stats19 2008 where 'vision affected by blind spot' was a contributory factor	Summerskill *et al.*, (2014)
Travelling alongside	Cyclist	Fatals	9	33.3%	Fatal police collision files for London 2007 - 2011	Talbot *et al.*, (2014)*

* Not carried forward to calculate target population data as case selection criteria excludes key population data that allows scaling up to EU level

Table 40: Collision distribution of KSI car occupant and KSI HGV occupant collisions involving HGVs by HGV manoeuvre type

Collision Scenario	Collision Distribution	Injured Party	Injury Severity	Database	Source
Side swipe (oncoming traffic)	10.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
Side swipe (lane change)	5.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	6.0%-9.0%	Car	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
Oncoming traffic (car front to HGV front)	35.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	13.0%-21.0%	Car	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
	35.8%	Car	Fatals	HVCIS 1997-2006	Robinson and Chislett, (2010)
Oncoming traffic (HGV front to car side)	5.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	11.0%-27.0%	Car	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
Intersection (car front to HGV side)	10.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	0.5%-13.0%	Car	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
Intersection (HGV front to car side)	15.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	0.5%-18.0%	Car	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
Rear end collision (HGV front to car rear)	10.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	7.5%-16.0%	Car	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
Rear end collision (car front to HGV rear)	10.0%	Car	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	6.0%-10.0%	Car	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
Single HGV	50%	HGV	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	21.0%-60.0%	HGV	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
HGV vs HGV head on	10%	HGV	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	0.0%-13.0%	HGV	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
HGV vs HGV rear end	20%	HGV	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	6.0%-79.0%	HGV	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)
HGV vs car	5%	HGV	KSI	Lyon and Gothenburg Accident Research databases	Volvo trucks, (2013)
	0.0%-2.0%	HGV	KSI	DEKRA, IVECO & CIDAUT databases (Volvo data excluded)	Welfers *et al.*, (2011)

Annex 1.3.3.3 Cars and HGVs

The main collision scenario for car to HGV collisions is car front to HGV front, accounting for 13-36% of car occupant KSI collisions (Table 40) (Welfers *et al.*, 2011;Volvo Trucks, 2013;Robinson and Chislett, 2010). These head-on collisions often involve very high relative speeds, with half of such collisions occurring at relative speeds (Δv) of more than 130 km/h (Knight, 2016).

HGV occupants are rarely killed or seriously injured in collisions with cars; up to 5% of collisions where the HGV occupant is killed or seriously injured involved a car whereas single vehicle HGV collisions account for up to 60% of KSI HGV occupant collisions (Volvo Trucks, 2013;Welfers *et al.*, 2011).

Annex 1.3.4 Vehicle and opponent speeds

When looking at the main collision scenarios involving VRUs it is important to understand the speed at which the pedestrian or cyclist is moving and the distance away from the front of the HGV they are in order to determine which safety measures would be effective in preventing such collisions from occurring.

In the scenario where the HGV is moving off, usually the VRU walks or cycles across the front of a stationary HGV to cross the road, but before they have safely crossed the front of the vehicle the HGV starts to move off (Robinson *et al.*, 2016). The worst case scenario of this type of collision is when the VRU is very close to the front of the vehicle as they are almost entirely in the vehicle blind spot. This distance can be as little as 0.3 m from the front of the HGV. Slower VRU moving speeds are also thought to lead to a worst case scenario and have been averaged to be around 5.2 km/h (Gates *et al.*, 2006).

An analysis of all fatal accidents involving HGVs and VRUs in France in 2006 found that in 48% of collisions the distance between the pedestrian's impact position and their final resting position was less than 5 m, indicating low impact speeds (Volvo Trucks, 2013).

Robinson *et al.,* (2016) reported that Schreck and Seiniger analysed German GIDAS data of cyclist collisions with HGVs and found that the HGV speed was less than 30 km/h in 90% of collisions and the speed of the cyclist was less than 20 km/h in 85% of collisions. The speed of the cyclists was greater than the speed of the HGV in 40% of the cases as the pedal cyclist was undertaking the HGV.

With regard to collisions involving HGVs and cars the relative speeds of the two vehicles are often much higher. As previously mentioned, the relative speeds of head-on car to HGV collisions are greater than 130 km/h in half of collisions (Knight, 2016).

Annex 1.3.5 Impact Configurations

The majority of pedestrian collisions involved impacts against the front of the HGV, with impacts to the sides or rear much less common (Table 41). The most common point of impact between pedal cyclists and HGVs, however, was found to be the side (Table 42). Similar to pedestrian collisions, passenger cars were also more likely to be impacted by HGV front ends (Table 43). These impact configurations correspond to the manoeuvre types mentioned in the previous section; pedestrians are most often killed or seriously injured when the truck is moving off and the most common point of impact is located at the front of the HGV. Similarly pedal cyclists are most commonly killed or seriously injured when the HGV is making a nearside turn and are most often involved in impacts to the side (the nearside in particular for HGVs).

Table 41: Point of impact of pedestrian on HGV

Source	Data	Injury Severity	All *n*	Front *n* (%)	Side *n* (%)	Rear *n* (%)
Robinson and Chislett (2010)	Annual average from Stats19 2006-2008	Fatal	72.0	50.0 (69.4)	14.0 (19.4)	4.7 (6.5)
Robinson *et al.* (2016)	Annual average from Stats19 2005-2014	Fatal	50.4	36.2 (71.8)	11.5 (22.8)	2.7 (5.4)
Knowles *et al.* (2012)	Police collision files for London 2006 - 2010	Fatal	27.0	22.0 (81.5)	1.0 (3.7)	4.0 (14.8)
Robinson and Chislett (2010)	Annual average from Stats19 2006-2008	Serious casualty	151.3	54.7 (36.2)	61.0 (40.3)	20.0 (13.2)
Summerskill *et al.* (2017)	Stats19 2010-2015	Casualties	1,228.0	558.0 (45.4)	546.0 (44.5)	124.0 (10.1)

Table 42: Point of impact of pedal cycle on HGV

Source	Data	Injury Severity	All *n*	Front *n* (%)	Side *n* (%)	Rear *n* (%)
Robinson and Chislett (2010)	Annual average from Stats19 2006-2008	Fatal	27.0	9.7 (35.9)	16.0 (59.3)	1.3 (4.8)
Robinson *et al.* (2016)	Annual average from Stats19 2005-2014	Fatal	17.9	5.7 (31.8)	10.8 (60.3)	0.5 (2.8)
Talbot *et al.* (2014)	Police collision files for London 2007 - 2011	Fatal	29.0	17.0 (58.6)	12.0 (41.4)	0.0 (0.0)
Robinson and Chislett (2010)	Annual average from Stats19 2006-2008	Serious casualty	72.0	19.3 (26.8)	46.7 (64.9)	4.0 (5.6)
Summerskill *et al.* (2017)	Stats19 2010-2015	Casualties	1,263.0	385.0 (30.5)	734.0 (58.1)	144.0 (11.4)

Table 43: Point of impact of passenger car on HGV

Source	Data	Injury Severity	All *n*	Front *n* (%)	Side *n* (%)	Rear *n* (%)
(Robinson and Chislett, 2010)	Annual average from Stats19 2006-2008	Fatal	146.3	99.0 (67.7)	20.7 (14.1)	25.7 (17.6)
Smith *et al.*, (2008)	Total collisions from Stats19 2003-2005	Fatal	531	397.2 (74.8)	64.8 (12.2)	67.4 (12.7)
Smith *et al.*, (2008)	Total collisions from Stats19 2003-2005	KSI	2457	1415.2 (57.6)	599.5 (24.4)	375.9 (15.3)
(Robinson and Chislett, 2010)	Annual average from Stats19 2006-2008	Serious casualty	501.3	273.7 (54.6)	128.4 (25.6)	92.3 (18.4)
Volvo Trucks (2013)	Lyon and Gothenburg Accident Research teams	Casualties	-	- (65.0)	- (15.0)	- (10.0)

When comparing the impact location of fatal and injured pedestrian casualties, impacts to the front of the HGV account for the largest proportion of fatalities, whereas impacts to the side of the HGV contribute to the largest proportion of injured casualties (Figure 23). When looking at HGV collisions involving pedal cyclists, however, there seems to be a slightly greater proportion of fatalities associated with pedal cyclists being struck by HGV front ends (Figure 24).

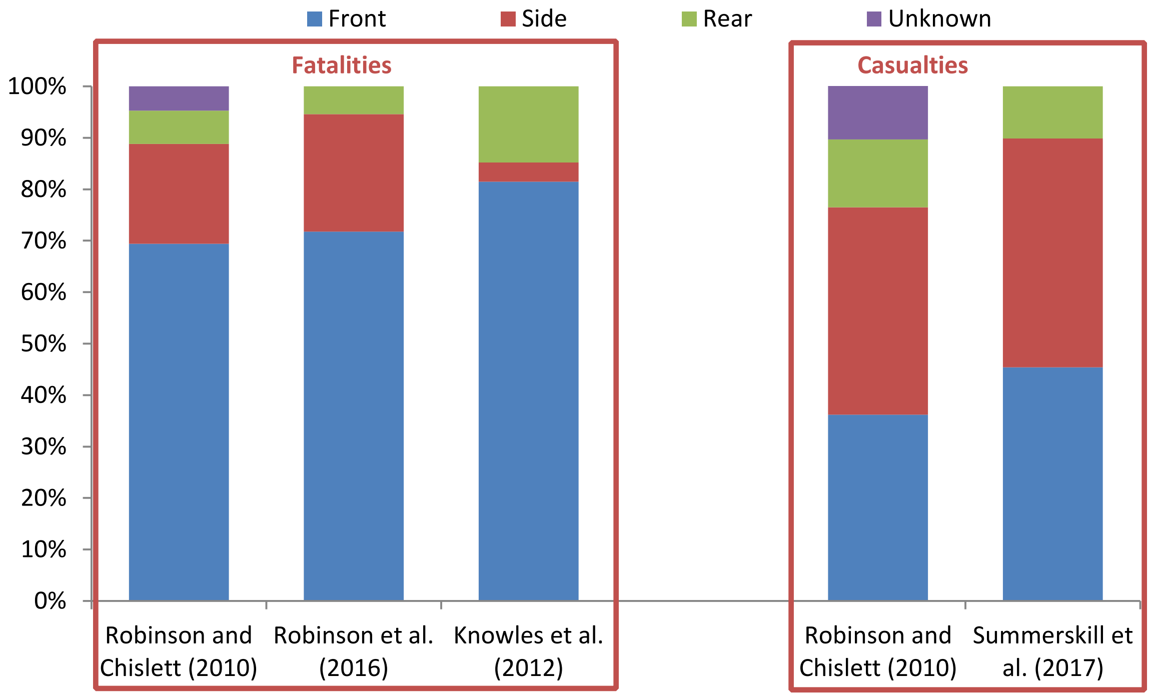


Figure 23: Distributions of first point of impact between pedestrians and HGVs

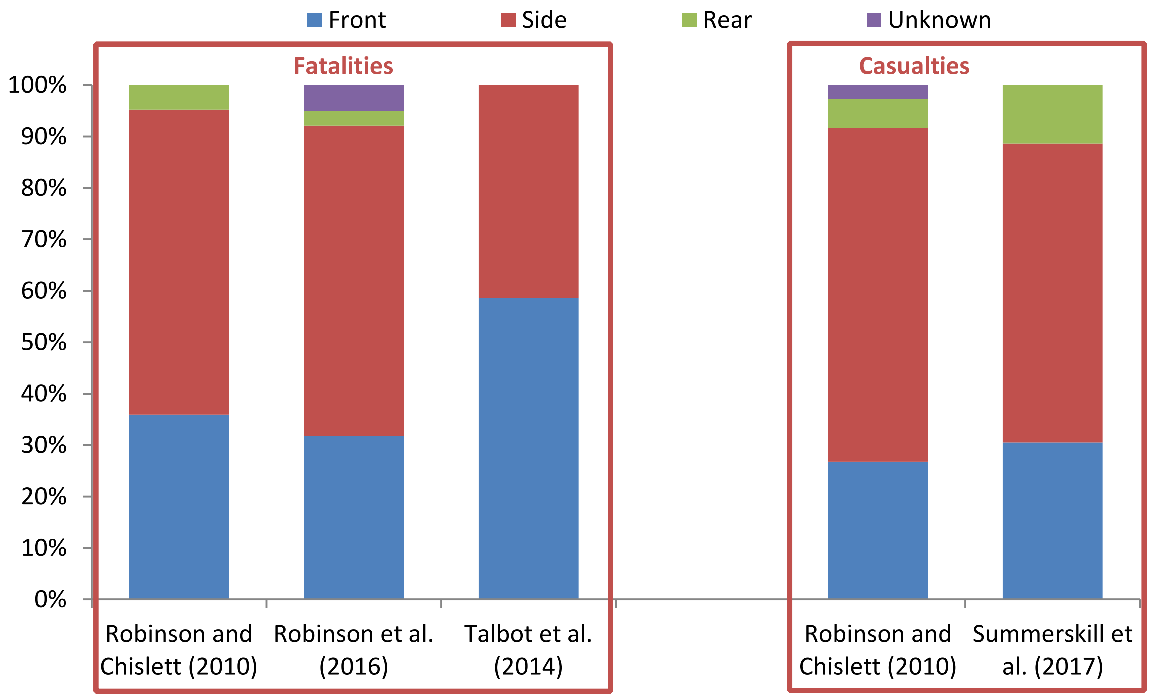


Figure 24: Distributions of first point of impact between pedal cyclists and HGVs

The majority of car occupant fatalities and injuries have also been found to involve the front of a HGV (Figure 25). Again a greater proportion of fatalities, when compared to injuries, were associated with passenger cars being struck by the front end of a HGV.

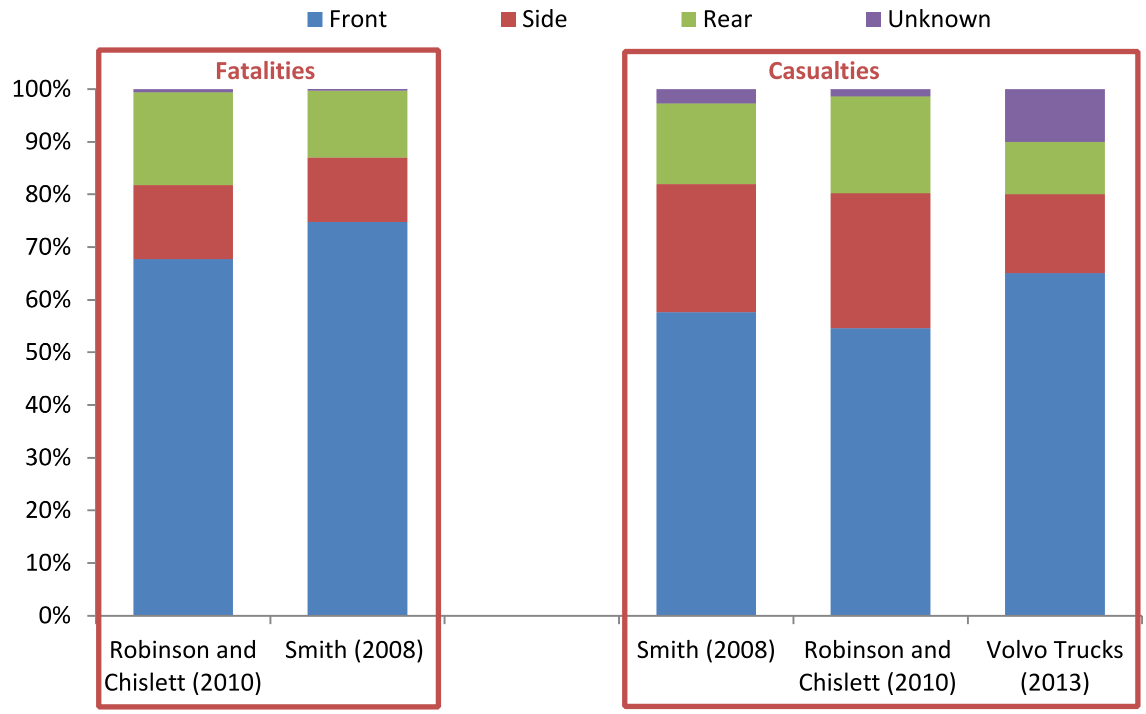


Figure 25: Distributions of first point of impact between car and HGVs where the collision has led to a car occupant fatality or injury.

When looking further into the collisions involving a car and the front end of a HGV, it was found that 36% of all car occupant fatalities arising from collisions with the HGV were the result of a head-on impact, 18.7% involved HGVs impacting the side of a car and 12.8% involved impacts to the rear of the car (Robinson and Chislett, 2010). These distributions followed a similar pattern for seriously injured car occupants, with 30.3% involving the front of the car, 12.1% involving the side and 12.2% involving the rear.

A summary diagram of the range of HGV impact points during collisions with pedestrians, cyclists and car occupants is illustrated below for all fatal (Figure 26) and injured (Figure 27) opponents. The impact point data from Knowles *et al.* (2012) and Talbot *et al.* (2014) has not been included in the summary diagrams as due to the fact that the data is not representative of the collision landscape due to reviewing fatal collisions only.

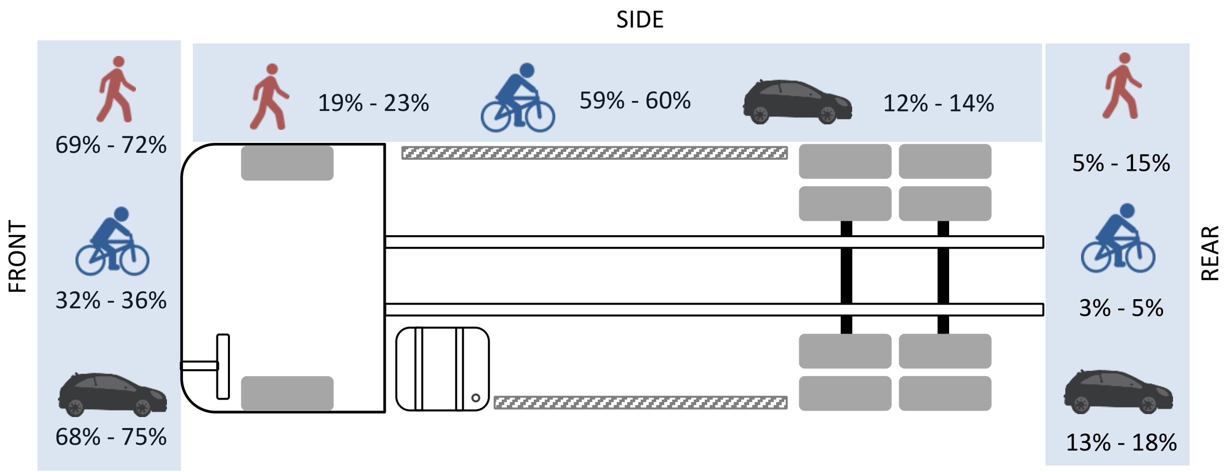


Figure 26: Distribution of fatal pedestrian, pedal cyclist and car occupant collisions with HGVs according to point of impact.

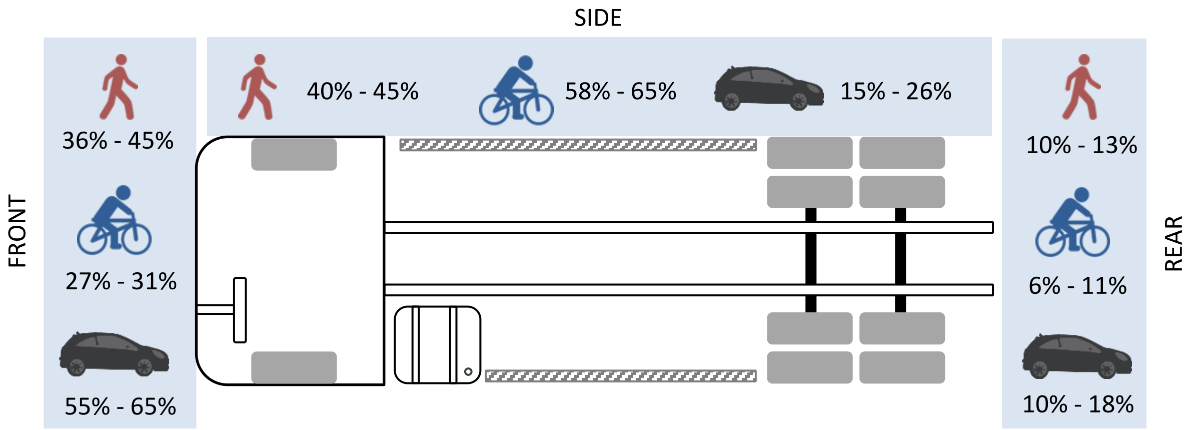


Figure 27: Distribution of injured pedestrians, pedal cyclists and car occupants in collisions with HGVs according to point of impact.

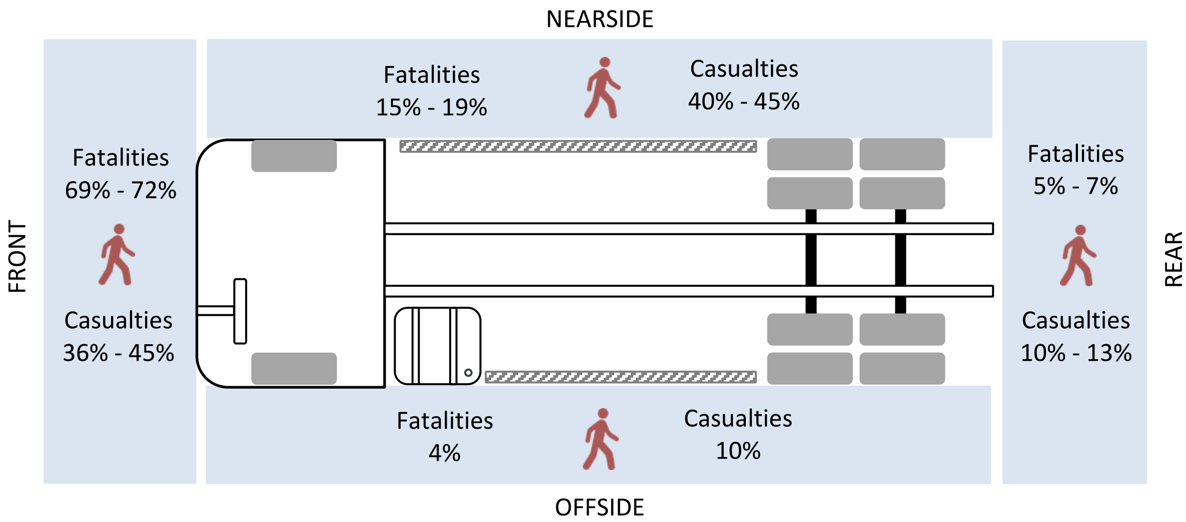


Figure 28: Distribution of impact point of pedestrians involved in collisions with a HGV

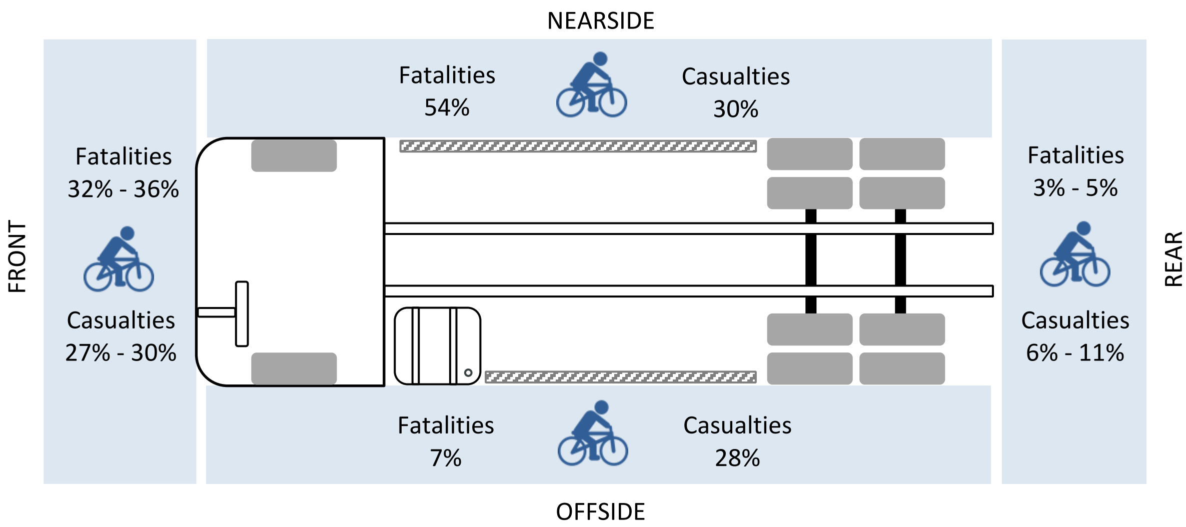


Figure 29: Distribution of impact point of pedal cyclists involved in collisions with a HGV

For pedestrians and cyclists the impact points were able to be further split into nearside (Figure 28) and offside (Figure 29) regions demonstrating that impacts with the nearside of a HGV are more likely to be fatal, or cause injuries, than impacts with the offside for both pedestrians and cyclists.

An in-depth study of fatal pedestrian collisions in London found the majority of collisions involved the pedestrian impacting the front of the vehicle, with a larger proportion of impacts to the nearside-front than to the offside-front (Figure 30) (Knowles *et al.*, 2012).

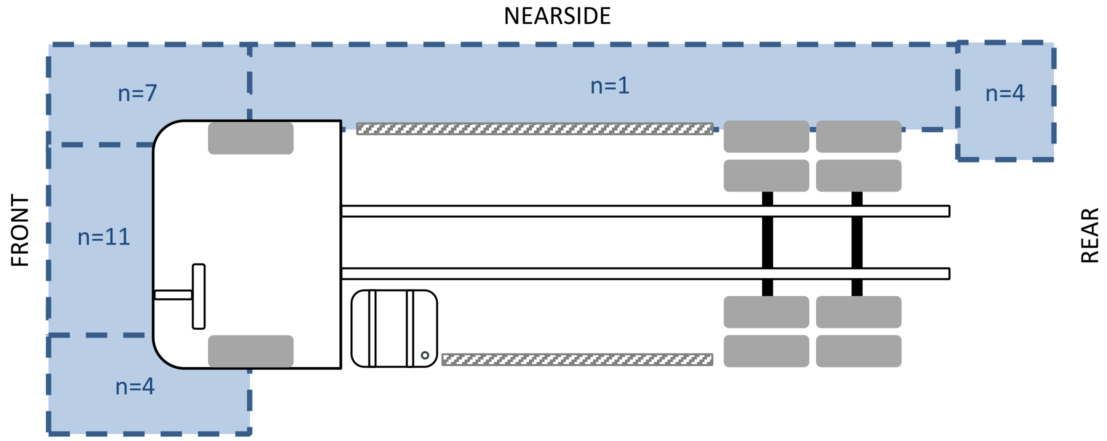


Figure 30: Impact points of pedestrians on fatal HGV collisions (Knowles *et al.*, 2012)

Three in-depth studies into pedal cyclist and HGV collisions were highlighted through the literature search, the impacts points of which can be seen in Figure 31. A study of fatal pedal cyclist collisions in London found that, in 29 collisions involving a HGV, the majority of cyclists impacted the front or nearside-front area of the HGV (Talbot *et al.*, 2014). In 13 cases the cyclist was run over by the front wheels and in nine cases the cyclists were run over by the rear wheels as the HGV was making a nearside turn. Eighteen police fatal collision files relating to cyclists killed by a HGV turning left were analysed, finding that two-thirds of collisions involved cyclists impacting the nearside-front of a HGV (including three ahead of the front axle and eight in line with or just behind the front axle) (Jia (2015), in Robinson *et al.* (2016)). It should be noted, however, that the majority of these collisions occurred in the Metropolitan Police area, so there is possible overlap between the cases analysed by Talbot *et al.,* (2014). Finally, 38 nearside turn collisions from the German In-Depth Accident Study (GIDAS) database and found that 61% of cases involved impacts to the front of the HGV and 24% involved impacts to the middle (Schreck and Seiniger (2014), in Robinson *et al.* (2016)).

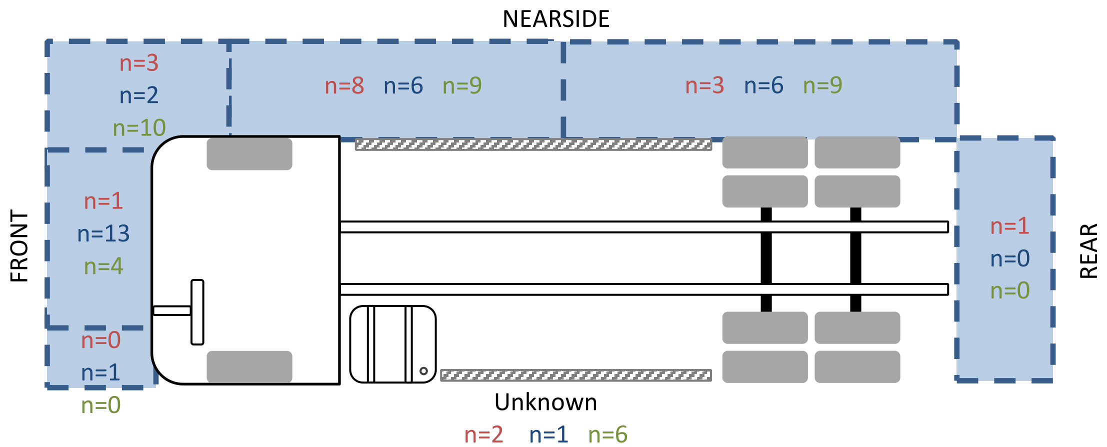


Figure 31: Impact points of pedal cyclists on HGVs (red - Robinson *et al.*, (2016) , blue - Talbot *et al.*, (2014) ,green - Schreck and Seiniger (2014))

Annex 1.3.6 HGV types

A study of fatal pedal cyclist collisions in London found that 30 out of the 53 collisions investigated involved a HGV, the majority of which were over 7.5 tonnes (89%) (Talbot *et al.*, 2014). Construction-type HGVs were most often involved, with tipper trucks, skip carriers and cement mixers involved in almost half of collisions (Figure 33). GB level data also shows that construction-type HGVs cause a large proportion of fatally and seriously injured pedal cyclists (Figure 33) (Delmonte *et al.*, 2013).

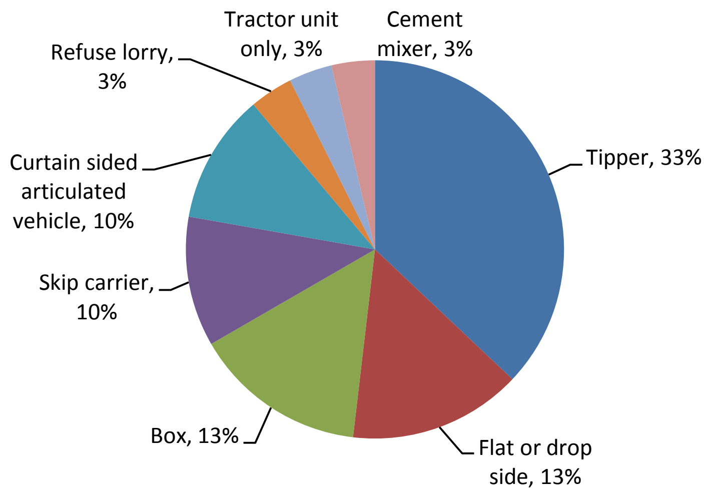


Figure 32: HGVs in collisions with fatally injured pedal cyclists in London by body type (Talbot *et al.*, 2014).

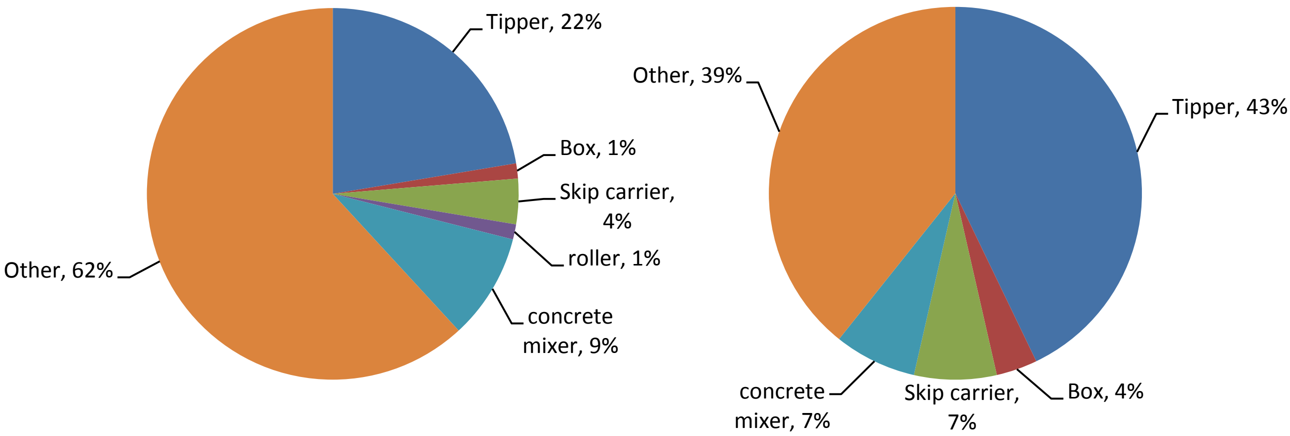


Figure 33: HGVs in collisions with fatally (left) and seriously injured (right) pedal cyclists by body type (Stats19 2008-11) (Delmonte *et al.*, 2013)

HGV length data has also been used as a proxy for different HGV types (Wismans, 2016), with short combination (≤12 m) representing rigid trucks, medium combinations (12.01-18.75 m) representing normal articulated HGVs and long combinations (18.76-25.25 m) representing dual tow HGVs. The STRADA database used by this study collected data on all collisions involving HGVs that occurred in Sweden between the years of 2003-2012. This research found that collisions in urban areas more frequently involved short combination HGVs, whilst collisions in rural areas more commonly involved longer combination HGVs (Figure 34) (Wismans, 2016).

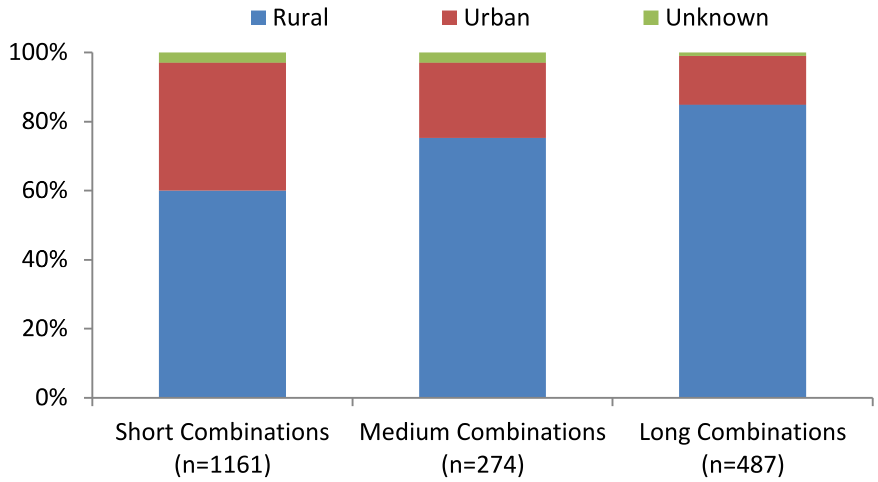


Figure 34: Collision location by length of HGV (Wismans, 2016).

When looking at the distribution of collisions involving HGVs and cyclists short combination HGVs contribute to the highest proportion of cyclist fatalities in comparison to medium and long combination HGVs. Similarly short combination HGVs are more commonly involved in collisions with pedestrians, followed by long then medium combination HGVs (Figure 35).

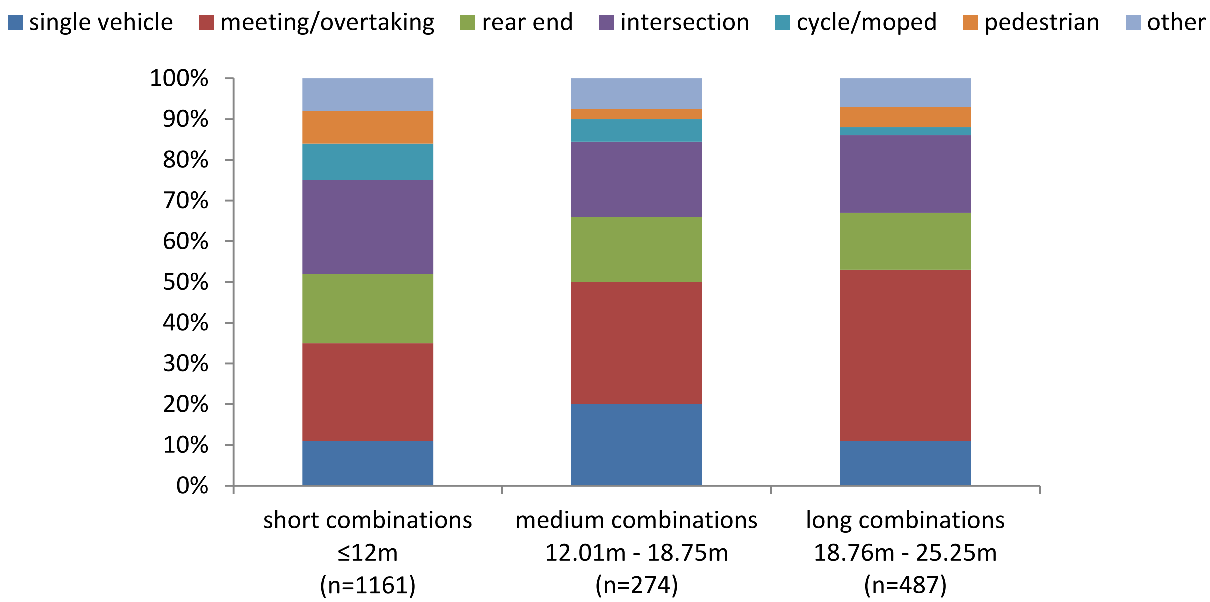


Figure 35: Collision type by length of HGV (Wismans, 2016)

Annex 1.3.7 Target Population Overview

The target populations relevant to each safety technology were calculated using the method described in Section 2.6 and are shown in (Table 44). The manoeuvres or impact regions most relevant to the safety measure are described and the proportion of the target population involved in these particular collision scenarios is presented.

Table 44: Summary of target populations defined by impact region relevant to safety technology.

Safety measure	Technology	Manoeuvre /Impact region*	Casualty	Fatalities		Serious Casualties	
				Proportion	Number	Proportion	Number
Direct Vision	Low Entry Cab Equivalent	MO, TNS, TOS	Pedestrian	27%	157	17%-46%	159-431
			Pedal Cyclist	53%	154	17%-54%	143-452
Indirect Vision	Camera/Detection Systems (Blind-Spot)	MO, TNS	Pedestrian	24%	141	17%-34%	159-319
			Pedal Cyclist	47%	137	19%-42%	143-351
	Camera/Detection Systems (360°)	MO, TNS, TOS, SSN, SSO	Pedestrian	30%-33%	174-192	20%-52%	187-487
			Pedal Cyclist	56%-59%	163-171	20%-60%	168-503
Secondary Passive	VRU impact protection	All frontal	Pedestrian	69%-72%	401-415	69%-72%	339-426
			Pedal Cyclist	32%-36%	92-104	32%-36%	225-256
	Front underrun protection	Head on	Car Occupant	36%	674	19%-35%	1220-2247
VRU Airbag	VRU /pedestrian airbag	All frontal	Pedestrian	69%-72%	401-415	36%-45%	92-104
			Pedal Cyclist	32%-36%	339-426	27%-31%	225-256

* Manoeuvre selected for the direct vision, indirect vision and front underrun protection for safety measures, and impact region selected for the secondary passive and VRU airbag. MO, moving off; TNS, turning to nearside; TOS, turning to offside; SSO, side swipe to offside; SSN, side swipe to nearside.

Annex 1.4 Estimates of Effectiveness

Annex 1.4.1 Overview

The effectiveness of a device or design feature is determined by how well the particular device or design feature works. Estimates of effectiveness may be calculated based on the percentage of people whose death or injury could have been prevented, or injury severity reduced, should the particular device or design feature be fitted to the HGV.

The purpose of this section of the Annex is to review the effectiveness of the range of devices or design features related to each of the five safety measures investigated in this project. The following sections therefore review the evidence base underpinning each of the safety measures including direct vision, indirect vision (mirrors, cameras, detection systems), frontal impact compatibility, front underrun protection and VRU airbag.

Annex 1.4.2 Direct Vision

In a study conducted by Loughborough University, Summerskill and Marshall (2014) found there are two key factors relating to a vehicles direct, and indirect vision, these are the vehicles cab height and glazed area. The study found the cab height of N3G category HGVs (off-road variants in excess of 12 tonnes) is on average 32% higher than the distribution variant of the same cab design. This means that the distance from the front of a truck that a pedestrian can remain hidden from the view of the driver is approximately three times greater than equivalent N3 distribution configurations and double the distance from the nearside of the HGV for cyclists (Summerskill and Marshall, 2014). To meet the demands of urban environments, most HGV manufacturers offer a Low Entry Cab (LEC) model in their product range. Summerskill and Marshall (2014) found that dedicated LECs, such as the Dennis Eagle Elite and Mercedes-Benz Econic, tend to provide the largest driver field of view for production trucks through digitally projecting the field of view available to the driver through windows and mirrors. Whereas LEC designs based on standard cabs have variable performance.

In a study conducted by Arup, 41 drivers were tasked with avoiding a VRU while driving a traditional and Low Entry Cab (LEC) HGV in a simulated urban environment (Milner and Western-Williams, 2016). These simulations observed that 43.3% of participants collided with at least one VRU whilst driving in a HGV with a traditional cab design, whereas only 26.7% of participants (11 collisions) had such collisions when in the LEC. The drivers had to undertake two scenarios, one whist driving normally and as second whilst completing a cognitive task. In a normal driving task improved direct vision reduced likelihood of collisions occurring involving:

- a pedestrian walking in front a HGV by 23%
- a moving bicycle and a HGV occurring by 7%
- a stationary bicycle and a HGV occurring by 7%

In a cognitive driving task improved direct vision reduced likelihood of collisions occurring involving a pedestrian walking in front a HGV by 40%, did not have any effect on collisions involving a moving bicycle and a HGV and increased the likelihood of a collision involving a stationary bicycle and a HGV occurring by 4%.

Unfortunately LECs would not make a suitable replacement to all N3Gs as their design is not optimised for off-road situations (Robinson *et al.*, 2016). The reduced cab height is achieved by moving the cab forward; creating a longer front overhang and reducing the vehicle's maximum approach angle. Moving the cab forward also reduces the amount of space for the engine and cooling which limits the vehicles engine size and power. Furthermore LECs do not use the typical 8x4 (two front and two rear axles) configuration used on conventional tippers; instead they use a tridem configuration (one at front and three at rear) this makes meeting 32 tonnes difficult because it does allow for much variation in the positioning of the centre of gravity position when fully loaded without exceeding the vehicles maximum axle weights. On the road, the longer cab contributes to less manoeuvrability in terms of overall swept path which could increase the risk to VRUs during turning manoeuvres.

Whilst LECs provide the potential to improve direct vision, the issue of the blind spots still remaining or the driver not looking correctly may mean that having a large field of vision is irrelevant. Using STATS 19 data, Cook *et al.* (2011a) found that 24% of fatal accidents involving VRUs were as a result of this so could not be reduced through by this safety measure. From this Hynd *et. al.* (2015) estimated that the remaining 76% (high effectiveness range) that could be affected by improved direct vision equated to 553 VRUs.

Loughborough Design School looked at the potential of removing or redesigning the large traditional dashboard featured in all current HGVs (Summerskill *et al.*, 2014). They found this had the potential to not only increase the internal useable volume of the cab but also lower the bottom edge of the windscreen height or allow extra space for additional windows. No current HGV has a central instrument panel or control console type cab layout but the feature is incorporated in to most modern concept vehicles.

Nearside (passenger side) door windows, are being adopted by many operators, especially in London (Pink, 2016b). This type of window is currently a retrofit option for the majority of HGV models, as a result there is no current standard method of fitment or positioning so the performance results can vary.

The TRL DVS study modified both their N3 and N3G CAD models to include a nearside window (dark green represents the visible area with an additional door window) (Robinson *et al.*, 2016). The window improved side vision but provided limited improvement to the rear. The window and revised dash board, improved the N3Gs score from 0.39 to 0.41 - 0.42 (zero star to one star) and the distribution configured N3 from 0.46 to 0.52 (two star to three star).

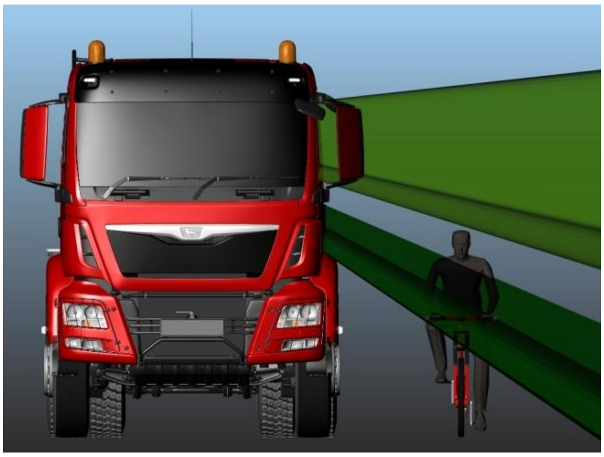


Figure 36: DVS N3G CAD model (Robinson *et al.*, 2016)

Simulations conducted by ARUP had similar conclusions to the TRL DVS report (Milner and Western-Williams, 2016). They demonstrated there was no evidence to suggest that an additional window improves the safety of VRUs in close proximity to a HGV. The report raises several issues including giving the VRU a false sense of security and the window does not help the driver identify a cyclist along the vehicle until they are adjacent to the window, by which point the cyclist is already in the danger area.

Another concern with this feature is the effect the passenger seat and passenger can have on the drivers view. No research has been conducted on this subject however the issue is raised in several reports.

Annex 1.4.3 Indirect Vision

Indirect vision, in the context of this project, refers to the indirect field of vision around the vehicle available to the driver through the aid of assistive devices such as mirrors or cameras or available to a sensor array through sensor-based detection systems. Because of this definition, the field of vision provided by such devices does not necessarily have to be provided in image form and can instead take the form of an audio-visual warning such as an alarm or flashing light.

Since the mid-2000s, three types of mirrors have become compulsory to supplement the main Class II rear view mirrors (see Figure 37).

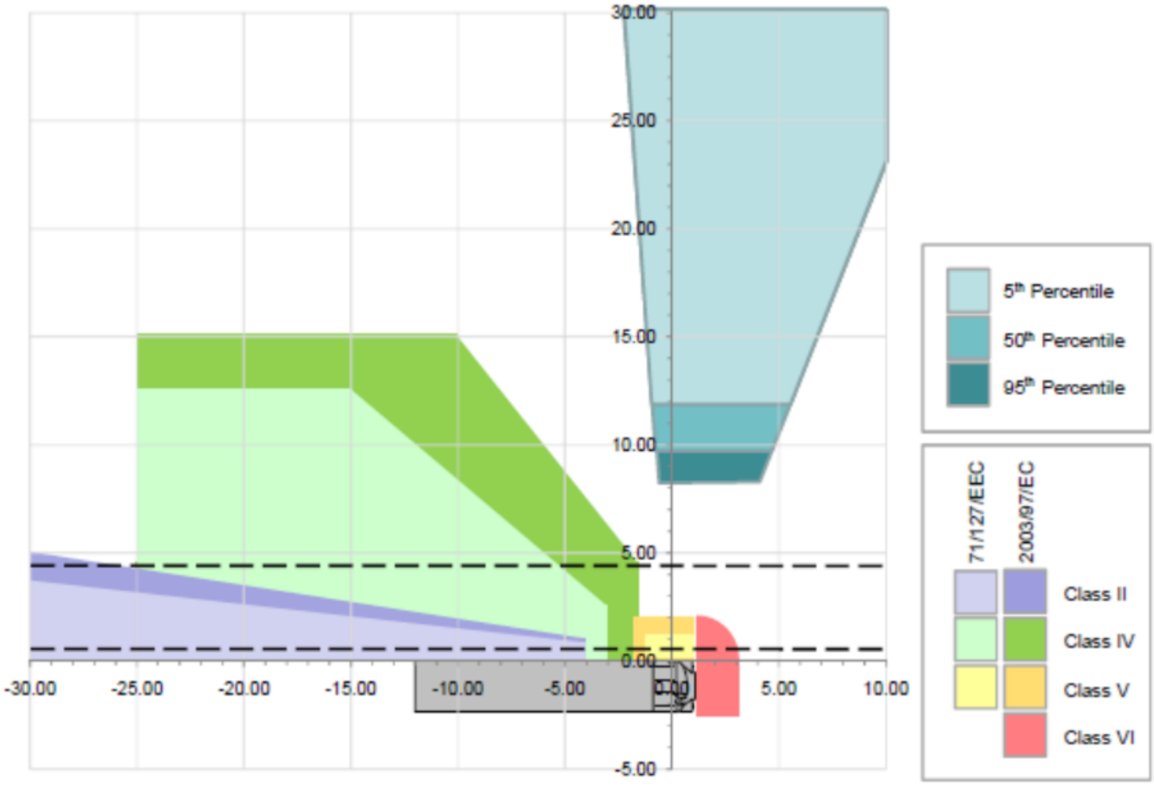


Figure 37: Field of view from the mandatory mirrors (of a Renault Magnum) and through the side window (Dodd, 2009)

A Class IV wide angle mirror is fitted to the nearside wing mirror cluster and provides a wide angle view of the side of the vehicle. Class V close proximity mirrors are also fitted to the nearside of the vehicle however they are mounted above the door and are used to detect pedestrians or vehicles moving parallel to the nearside of the vehicle. These mirrors are particularly useful in manoeuvres which involve the HGV turning left.

The Class VI mirror is a front mounted wide view device intended to assist drivers in locating VRUs and vehicles directly in front of the vehicle this helps the driver in manoeuvres such as starting from rest e.g. at a zebra crossing.

These zones are achievable if the mirrors are adjusted correctly however this is not always the case and often problematic (Cook *et al.*, 2011b). Many drivers often find the mirrors are either mounted too high to be reached without steps or, in the case of Class II and IV mirrors, too far forwards to be reached easily through the driver's window. Unfortunately even if the mirrors are correctly adjusted a vehicle fitted with all six mirrors will still have blind spots. To solve this issue, manufacturers have come up with several supplementary integrated or retrofit devices to assist drivers such as cameras and sensors.

Cameras can be utilised in several ways when installed onto HGVs. They may be used as a replacement for mirrors (as described in Reg 46) or as a supplementary method of indirect vision. In addition cameras can be used as sensors to detect and alert the driver to potential hazards without displaying the image. Early Camera Monitoring Systems (CMS) filled dashboards with a variety of single view displays, these not only overloaded the driver with information, they also blocked the windscreen. Today multi-camera systems can blend views together providing a 360° bird's eye view that can swap to a full screen display of the relevant angle during a certain manoeuvre. This reduces the amount of screens and data to look for the driver to look at. Recent concepts have also started to locate screens in areas which are more natural to look at such as the A-Pillar for cameras supplementing the wing mirrors.

Truck manufacturers offer both semi and fully integrated camera systems on certain new models. The Volvo FH, FM and FMX Series allows the capability to connect up to four exterior cameras to the secondary information display within the cab, the cameras can be installed separately as an aftermarket solution or ordered as an accessory and fitted to the vehicle by Volvo (Volvo Trucks, 2014). Similarly Mercedes-Benz offer pre-installation of the hardware required for a reversing camera that can be ordered as an accessory or retrofitted using an aftermarket solution (Mercedes-Benz, 2016). The reversing camera image is displayed within the instrument cluster.

There are also a wide variety of aftermarket solutions; systems are currently available that are certified to replace Class V and VI mirrors, as well as multi-camera systems that can provide a 360° view of around the vehicle. Images from multiple cameras can be stitched together images to provide a 360° bird's eye view of around the vehicle in one image, without subjecting the driver to extra sensory overload that would be associated with multiple monitors or mirrors. Other systems use one monitor and alternate between each camera view, allowing the most important view to be displayed according to the vehicle manoeuvre and speed. For example when the HGV is put into reverse the rear view camera image will be displayed.

The Brigade Backeye 360 system for example uses four cameras. It has been certified to replace class V and VI mirrors and leaves no blind spots. The driver interface displays one image to prevent sensory overload (Brigade, 2017).

Camera monitoring systems have now reached a sufficient point in development that many can offer a very high quality display (Cook *et al.*, 2010). However there are certain environmental situations, amongst others, where the technology is still too immature to completely replace mirrors such as adapting to extreme variations in sunlight e.g. night-time driving on unlit roads, or images being "burnt-out" when the camera faces direct sunlight and the view from a low mounted camera being obscured by spray.

In a similar sense to cameras there are both integrated and aftermarket sensor-based detection solutions available. Rather than providing a visual image to the driver of the area around the vehicle the sensor based systems provide a warning to the driver in the form of audible, visual or haptic feedback (vibrating of the steering wheel). There is currently no regulation for sensor based detection systems such as LIDAR, RADAR, ultrasonic and camera based driver warning systems. Aftermarket VRU detection systems were to have a smaller detection range (0 m to 3 m) compared to integrated systems (0 m to 250 m). Certain detection systems also include an active response to a hazard by applying the brakes or adjusting the steering automatically, this report will only examine the passive systems that provide a warning to the driver.

The Brigade ultrasonic Obstacle detection system can detect a potential hazard in less than 200 ms (Brigade, 2017). The package comprises of five sub systems; Frontscan uses four sensors with up to a 2.0m range; Cornerscan uses three sensors with a detection range between 0.6 to 1.0m; Stepscan uses two sensors and has up to a 1.0m range, Sidescan with four sensors with a 1-1.5 m detection range and Backscan. To prevent false alarms the product has an Environment Learning Mode from sections of permanent bodywork that intrude in the first 100cm of the detection zone.

Infra-red technology can be utilised in the form of cameras during low light conditions. Using these devices, a driver can see between 3-7 m in front of the vehicle (Brigade, 2017).

The main advantage of sensors is that they are always looking in the correct direction. Mirrors can easily be incorrectly positioned and driver not always monitoring correct mirror at the right time given that there are six or seven mirrors (Dodd, 2009). Camera or sensor based systems are correctly positioned to view particular blind spot and are continuously monitoring so can provide driver with a warning, independent of what the driver is doing. There is however the risk of the system giving false negative responses, or positive responses in non-urgent situations. This can lead to the driver doubting the system and a slower response during a time critical event in the future.

However, sensors may not consistently correctly identify and warn of pedestrians or cyclists. Rosen (2013) found that pedestrian and cyclist AEBS detection rates ranged between 42% and 58%. If the sensors do activate correctly the driver may not necessarily react accordingly to prevent the collision from occurring. To account for this a driver reaction factor based upon a human-machine interface factor of 80%, as recommended by Kuehn *et al.* (2009), which takes into consideration the response rate of the driver to positive detections of “at risk” VRUs, should be applied to obtain the overall effectiveness of a detection system.

Indirect vision devices share many common problems. Taoka (1990) calculated the mean glance time into a single mirror to be just over a second. Their investigation showed there is a 0.32-0.34 s travel time between mirrors. This means the length of time for pre-manoeuvre side glances (looking at all mirrors and using the direct vision available) could take between 4-6 seconds. This excludes longer glances at certain mirrors and checking the instrument panel. Furthermore, at the time of writing only three mirrors were required on a vehicle.

Failure to look or look correctly (e.g. Incorrect mirror positioning) is a major issue which can be mitigated to a certain extent with sensors that cover key blind spots (Cook *et al.*, 2010). However, even if the driver is looking in the correct direction for a manoeuvre, interpreting the available data (determining where the VRU is relative to the section of vehicle displayed) can still add to the overall driver reaction time (Arup, 2016). In a recent study assessing HGV driver reaction times in real-life environments, Arup (2016) found drivers reacted on average 0.7 seconds slower if the VRU was viewed through an indirect feature or device, such as a camera monitor, compared to directly through a window. This makes a major difference in key manoeuvres, such as pulling off. As this additional thinking time could add up to 1.5 m of extra travel when the vehicle is travelling at 5 mph and up to 4.7 m at 15 mph.

Annex 1.4.4 VRU Impact Protection

VRU impact protection concerns the structural components located at the front end of the HGV that optimises opponent compatibility and prevent run over events during frontal collisions involving VRUs.

In the early 2000s APROSYS demonstrated that the HGV nose cone concept would be most effective at protecting VRUs at impact speeds below 30 km/h (Feist and Faßbender, 2008). At this speed range approximately 80% of VRUs end up underneath the HGV, by deflecting them away with the cone this is prevented. Additional numerical simulations also indicated the VRU would encounter a less severe secondary impact when they hit the ground if they were guided by a nose cone.

Following on from this work, Welfers *et al.* (2011) predicted the potential VRU fatality reductions of the FKA HGV concept (based on the APROSYS nose cone see Figure 54 in Annex 3.5). The predicted figures were based on target population numbers from 2005–2007. The design was 70% effective at preventing VRU fatalities when travelling ≤40 km/h, 30% at 40-50 km/h and 0% at speeds >50 km/h. This equates to 232-296 pedestrians or 42-63% of VRU fatalities in the target population and does not include casualties relating to improved direct vision.

Robinson *et al.* (2010) calculated the number of VRU fatalities that could be prevented annually in GB with varying lengths of extended front ends. An increase of 0.2 m was estimated to prevent 15% of VRU fatalities; 0.5 m prevented 29% of fatalities and 1 m prevented 47% of fatalities.

Annex 1.4.5 Front Underrun Protection

Front Underrun Protection (FUP) systems play a key role in collision energy absorption. There are two main types; rigid and energy absorbing. Transport and Environment (2016) estimated energy-absorbing frontal underrun protection systems (EA-FUPS) have the potential to save up to 369 lives per year from car and HGV occupants in the EU27.

Robinson *et al.* (2010) analysed the effects of improving car and HGV occupant safety through the use of EA-FUPS and crumple zones. The study estimated the casualty savings (for GB), if all HGVs were equipped with EA-FUP systems, could be between 3-12 (6-22% of car occupant fatalities involved in frontal car-to-HGV impacts). HGV crumple zone were estimated to reduce between 2-6 (13-38%) HGV occupant fatalities involving a frontal impact with another HGV or heavy object.

As part of the VC-COMPAT project, Gwehenberger *et al.* (2004) estimated the potential casualty savings gained by fitting EA-FUP systems to HGVs in EU-15. By scaling up case-by-case analysis of in-depth accident data from six European countries, and the mandatary fitting of rigid FUP as the baseline for this piece of work, the team estimated EA-FUP systems could prevent between 190-204 fatalities (10-11% of car occupant fatalities involved in frontal car to HGV impacts) and 1,497 seriously injured (30% of serious car occupant casualties involved in frontal car to HGV impacts).

Using the range of effectiveness estimates for EA-FUP systems and HGV crumple zones from the studies by Robinson *et al.* (2010) and Gwehenberger *et al.* (2004) and using up to date target population at the time of writing, Hynd *et al.* (2015) estimated the EU-27 casualty saving for passenger car occupant fatalities could be between 128-175 per year and 41-194 per year for HGV occupants.

Another outcome of the APROSYS SP2 study was the safety bar concept (see Figure 55). This was an Expanded Polypropylene bull bar style add-on safety device designed to reduce the forces from the initial impact (Feist and Faßbender, 2008). Tests conducted using a prototype mounted on a HGV and a crash test dummy demonstrated that the bar could reduce the HIC15 by up to 91% from 696 to 66; the peak head accelerations by 64-68%, the cumulative 3 ms acceleration value for both the chest and Pelvis by up to 51%, the sternum deflection by up to 42% and the femur peak accelerations by up to 85%. This could be achieved without adding to the VRU throwing distance (the distance between pre and other post VRU position and other post primary impact injuries (Feist and Faßbender, 2008).

FUP is not the only way of reducing car and HGV occupant fatalities; extended front end designs have also been shown to be beneficial. The advantages of an enhanced front end design have been known for nearly two decades. In 1999 Scania claimed their Crash Zone Concept (see Annex 3.4) could reduce the 4000 EU HGV to car frontal collision related car occupant fatalities by 200-400 annually (Commercial Motor Archive, 2009a;Commercial Motor Archive, 2009b).

Robinson *et al.* (2010) calculated the number of fatalities that could be prevented annually in GB with varying lengths of extended front ends. The fatality savings estimates were based on annual fatality rates of car occupants killed in HGV collisions, based STATS19 data between 2006 and 2008 and HVCIS data between 1997 and 2007. An extension of 1 m was found to prevent 2-5 car occupant fatalities a year (in GB) if applied to all articulated HGVs and all HGVs respectively.

Knight (2016) built upon the work carried out by Robinson *et al.* (2010) and estimated that 670 car occupants across the EU would be killed in head on collisions with HGVs in 2013 and 1500 would be injured by scaling up Stats19 data from 2006-2008 to European levels. In the same study it was found an increase in front end length of 0.2 m could have the potential to prevent between 5-15% fatalities and between 40-55% of serious injuries in the EU if a 100% fitment rate was assumed. A 0.4 m increase could reduce 6-17% of fatalities and 45-60% of serious injuries, a 0.6 m increase could reduce 8-20% of fatalities and 50-60% of serious injuries and a 0.8 m increase could reduce 10-27% of fatalities and 55-65% of serious injuries.

Strandroth (2009) reported incorporating a 0.75 m deformation zone on a HGV fitted with AEBS could prevent 25 fatalities per year in Sweden. This would halve the number of car occupants killed in head on collisions.

Numerous papers including Feist and Faßbender (2008) and Robinson *et al.* (2010) have stated that a feature or device integrated in to the design of the vehicle from its inception is most effective at improving HGV frontal impact compatibility compared to a retrofit add-on feature.

Annex 1.4.6 Vulnerable Road User Airbag

The effectiveness of VRU airbags has been difficult to determine because of the lack of systems currently in existence. There are currently no frontal VRU airbag systems on the market for HGVs. A design was proposed in APROSYS SP2 but the idea was not taken forward (Bovenkerk and Fassbender, 2006).

Yamazaki and Redza Ramli (2013) analysed the impacts on adult and child secondary passive protection if a lower bumper stiffener and VRU airbag are installed to the front of a HGV, using MADYMO crash analysis software, impacting a pedestrian at a range of speeds, impact angles and gait positions. The airbag design is intended to reduce injuries in the pedestrians head and chest. To maximise deploying time, the necessary sensors are fitted to the extruded front bumper and the airbag is installed behind the front panel of the HGV. The study found, in the case of the child, the airbag could reduce the HIC value from 416.9 to 121.3, the thorax acceleration from 69 g to 39.6 g and left femur load from 1.25 kN to 1.1 kN. The right femur load remained at 0.7 kN. The paper did not provide sufficient adult baseline information to draw any adequate conclusions for this VRU category. It also assumed that the pedestrians head hit the airbag each test. Yamazaki and Redza Ramli (2013) found a single airbag was not sufficient to protect all pedestrians so recommended fitting two airbags to the front of HGVs, one for adults mounted between 1.4 m – 1.6 m from the ground and one for children mounted 0.8 m – 1.2 m.

In a project commissioned by the Dutch Cyclists' Union and the Dutch Ministry of Transport, TNO tested two types of external airbags for cars to be evaluated by the EuroNCAP beyond NCAP protocol (de Hair-Buijssen *et al.*, 2010). A pedestrian airbag, designed to cover the lower section of the windscreen and A Pillars, and a VRU airbag that covers the full windscreen to protect cyclists as well as pedestrians. AEBS was used as a benchmark for performance. The effectiveness study found the VRU airbag was most effective at preventing VRU fatalities but AEBS was better at reducing serious injuries. All three technologies (VRU airbag, pedestrian airbag and AEBS) were equally as effective at preventing pedestrian fatalities.

A key safety issue hindering the implementation of large airbags is that they must leave a sufficient amount of non-covered windscreen to allow the driver to safely bring the vehicle to a halt. This might not be an issue for a standard flat fronted distribution cab but could be an issue for a LEC of an enhanced TFED with additional glazing.

VRU airbags for cars are at a more advanced stage of development. Volvo claims their system for their V40 model can reduce the number of pedestrian fatalities by 5% and serious injuries by 14% (Volvo Car Group, 2017). In a series of tests conducted by the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MILT) and the National Traffic Safety and Environment Laboratory (NTSEL), The HIC 15 value recorded for a pedestrian in a collision with a V40 with a pedestrian airbag compared to a vehicle without the device, was reduced from 8000 to approximately 250 (MLIT and NTSEL, 2015).

These studies are using systems developed for cars therefore the effectiveness cannot be directly transferred across to HGVs. Detection and inflation time is critical, especially for large flat fronted vehicles as they do not have the period of time between first point of contact and head impacting the vehicle which bonneted vehicles have to react (Yamazaki and Ramli, 2013). A Land Rover Discovery Sport airbag takes 60 ms to inflate (Land Rover, 2016). One method of solving this issue is having smaller airbags in strategic places on the vehicle. Smaller airbags fitted to the front corners will not only inflate faster but could supplement other technologies such as AEBS. AEBS object detection is most reliable directly in front of the device (angle of detection), the further to the side the potential threat is the less certain the system is of the threat. This is a major short coming when the vehicle is turning as it is often the nearside corner which is the first point of impact and potentially out of range.

Pedestrian airbags are also being considered in the light urban rail industry (Bombardier, 2015). In 2015 Bombardier Transport incorporated their Driver Assistance System (DAS) into their vehicles which perform passenger services in Frankfurt. The system uses two stereo cameras and audible warnings to give the driver advance warning of a possible collision with a pedestrians or cyclist. If the driver fails to brake in time the tram can brake automatically and the Body Guard airbag system is deployed to prevent them from falling underneath the tram (similar to a HGV Front Underrun Protection Device). This type of airbag design is transferrable to HGVs however no results of its effectiveness are currently available.

Annex 1.4.7 Effectiveness Overview

The overall effectiveness values estimated for fatally and seriously injured casualties are summarised in Table 45. Individual technology effectiveness values were obtained from the literature and where applicable correction factors were applied to determine an estimate of overall effectiveness using the method described in Section 2.6. The below correction factors include the combination of the sensor activation, driver reaction and coverage factors by using values abstracted from the literature and presented in the previous subsections.

Table 45: Estimated overall effectiveness of safety measures calculated from technology effectiveness with a correction factor applied.

	Casualty	Fatalities			Serious Injuries		
		Technology effectiveness (%)	Correction factor (%)	Overall effectiveness (%)	Technology effectiveness (%)	Correction factor (%)	Overall effectiveness (%)
Direct Vision [DIR]							
Low Entry Cab Equivalent	Pedestrian	77-88	-	**77-88**	77-88	-	**77-88**
	Cyclist	0-20	-	**0-20**	0-20	-	**0-20**
Indirect Vision [IDV]							
Detection System (Blind-Spot)	Pedestrian	100	38-40*†	**38-40**	100	33-34*†	**38-40**
	Cyclist	100	42-46*†	**42-46**	100	26-27*†	**42-46**
Camera System (Blind-Spot)	Pedestrian	100	3-20*	**3-20**	100	3-20*	**3-20**
	Cyclist	100	3-20*	**3-20**	100	3-20*	**3-20**
Detection System (360°)	Pedestrian	100	38-40*†	**38-40**	100	33-34*†	**33-34**
	Cyclist	100	42-46*†	**42-46**	100	26-27*†	**26-27**
Camera System (360°)	Pedestrian	100	17-33*	**17-33**	100	17-33*	**17-33**
	Cyclist	100	17-33*	**17-33**	100	17-33*	**17-33**
VRU Impact Protection [VIP]							
Extended front end (0.5 m)	Pedestrian	29	-	**29**	29	-	**29**
	Cyclist	29	-	**29**	29	-	**29**
Extended front end (1.0 m)	Pedestrian	47	-	**47**	47	-	**47**
	Cyclist	47	-	**47**	47	-	**47**
FKA front end design	Pedestrian	42-63	-	**42-63**	42-63	-	**42-63**
	Cyclist	42-63	-	**42-63**	42-63	-	**42-63**
Front Underrun Protection [FUP]							
Extended front end (0.4 m)	Car occupants	6-17	-	**6-17**	45-60	-	**45-60**
Extended front end (0.8 m)	Car occupants	10-27	-	**10-27**	55-65	-	**55-65**
VRU Airbag [VAB]							
50% coverage & inclined face	Pedestrian	36-44	50†Δ	**18-22**	30-46	50†Δ	**15-23**
	Cyclist	19-49	47-53†Δ	**9-26**	28-38	47-53†Δ	**13-20**

* Driver reaction factor applied; † Sensor activation factor applied; Δ Coverage factor applied.

Annex 1.5 Estimates of Cost

Annex 1.5.1 Overview

The aim of this section is to determine the potential costs of implementing technology in each of the safety measures. There are many factors which contribute to an overall figure including product development, installation (fitment, vehicle downtime and expertise) and the timescale for introducing a new standard (Robinson *et al.*, 2016).

Annex 1.5.2 Direct vision

A cost benefit analysis conducted by Arup (2016), using data collected in a consultation with a selection of HGV manufacturers, provides an indication of the development cost for manufacturers, at different levels of production, wanting to produce vehicles with improved direct vision. The cost ranges were split into three categories, Manufacturer 1 (a high volume manufacturer (40 – 50,000 vehicles per year) with no LEC in their product range), Manufacturer 2 (a high volume manufacturer with a LEC in their product range) and Manufacturer 3 (a low volume manufacturer (1000 – 2000 vehicles per year) with a LEC in their product range). The cost of developing a completely new vehicle for Manufacturer 1 could be as high as €2 billion of which approximately €1 billion could be spent on direct vision. As manufacturer 2 has experience in the field, it was estimated they could design a completely new vehicle for €1 billion. This could be further reduced if they used carry over parts from previous models to €100 -500 million. The cost for manufacturer 3 could range between €16 - 23 million. The costs per vehicle associated with improving direct vision were estimated to be €3,500 - €10,000.

To the HGV operator, the price for a HGV with improved direct vision will be higher. The Mercedes–Benz Econic costs £65-100,000 (Dennis Eagle LEC’s are priced at a similar level) (London Cycling Campaign, 2013). Low Entry Cabs cost between £10-30,000 more than a conventional cab (Arup, 2016). This is because less of vehicles of this class are produced and require specialist components such as the gearboxes because their powertrain has a different package compared to most HGVs (Robinson *et al.*, 2016).

Near side (passenger side) door windows are currently a retrofit option for the majority of HGV models. TfL estimate that the installation cost for the operator could be between £1000-1500 (TfL, 2016).

Transport Engineer (2016) compared the prices and specifications of existing near side door windows. Products discussed included; the Kel truck Cycle Safety Door which costs £995 ex-VAT and takes two to three days to fit. This feature can be retrofitted to all Scania models due to its rubber fitting and is the same product used in the Scania Urban Tipper Concept. Scania South East equivalent CLOCS compliant safety window for P and R cabs costs £1295. Volvo also offers a side window for their FM cab which costs £1500. Renault D has the option of a factory fitted extended lower window for £350, The Volvo FE and FL models have a similar option costing the same. This is an indication of what the prices could be if there is a wider uptake of the feature in the initial design of HGVs.

There is no cost information publically available to quantify the difference in cost between an enhanced TFED without regulated vision and an enhanced TFED with regulated vision. To provide a proxy for this cost, values were based on those used for the VIP and FUP safety measures due to their similar implementations. The VIP safety measure provided the greatest estimated cost range per vehicle of €400-600 (Feist and Faßbender, 2008).

A summary of the cost figures in this section can be found in Table 46.

Table 46: Direct Vision Design Feature Costs

Source	Device/feature	Cost
(Arup, 2016)	Improved direct vision	€3,500 - €10,000
(London Cycling Campaign, 2013)	Low Entry Cab	£65,000-£100,000
(TfL, 2016)	Retrofitted nearside door window	£1000-£1500
(Transport Engineer, 2016)	Lower door window	£350

Annex 1.5.3 Indirect vision

The price range for a Camera Monitoring System was between £400- £3000. Cook *et al.* (2011b) estimated the average cost of a basic Camera Monitoring System is £490 per vehicle, including £70 installation. Since the time of writing, cameras have improved; a mid-range 360° (four 185°cameras) blended bird's eye view system can cost up to £1700 (excluding installation) (Trailer vision, 2017). More sophisticated blind spot Camera Monitoring Systems can reach £3000 depending on the manufacturer and system capability (CLOCS, 2016).

The lowest cost of a camera and monitoring system from Commercial Motors (2017) was found to be €283, with every additional camera costing an extra €170. To work out a system cost it was assumed that a CMS that provided view of the blind spots only would require two cameras whereas a CMS that provided a 360° view would require four cameras. An upper boundary cost estimate for a 360° CMS was found to be €1695 based on costs specific to an aftermarket solution from Brigade (2017)

Sensors also have a large price range because of the vast range of products and capabilities available on the market. A basic aftermarket sensor system can cost an operator as little as €150 (Knight, 2011). However a more sophisticated driver alert system could cost up to £1185 per vehicle including £430 to install the system to the vehicle (Cook *et al.*, 2011a).

The costs for an ultrasonic sensor system by Commercial Motors (2017) and HGV Direct Parts (2017) were found to be between €147 and €215. It is assumed that for a blind spot detection system three sensors are required whereas for a 360° detection system a total of 8 sensors will be required.

A summary of the total aftermarket costs for installing indirect vision devices can be seen in Table 47.

Table 47: Indirect Vision Aftermarket Device Cost per Vehicle

Technology	Costs (€)		
	First system/device	Additional cameras /sensors	Total per vehicle
Camera Systems (360°)	283	680	963
Camera Systems (Blind-Spot)	283	340	623
Detection Systems (360°)	147-215	1029-1505	1176-1720
Detection Systems (Blind-Spot)	147-215	294-430	441-645

Annex 1.5.4 VRU Impact and Front Underrun Protection

An estimate for the cost of a VRU Impact Protection device was taken from the APROSYS SP2 Safety Bar concept. The safety bar is a relatively simple add-on feature which costs approximately €400-600 (Feist and Faßbender, 2008).

There is little information in the cost of FUP systems on extended front end HGVs. The cost for improved secondary passive safety rises with the level of protection. Edwards *et al.* (2007) estimated current rigid underrun devices cost between €120-150 and an Energy Absorbing Front Underrun Protection Device would cost an additional €100-200 (plus a further €1-3 million for development, certification and production preparation).

Knight (2014) compared the cost of implementing an enhanced front underrun protection for a revised front-end design with revising the front end design without the enhanced FUP requirements. The additional costs for introducing energy absorbing FUP systems were estimated to be €220 - €350 per vehicle.

Robinson *et al.* (2010) found that when taking into consideration number of lives saved, emissions, fuel consumption and operating costs that a 0.2 - 0.5 m increase of front end length would save between £18.7 - £30.5 million per year in Great Britain respectively. However, whilst the 1 m increase in length provided the potential to reduce the greatest number of fatalities the costs outweighed the safety benefits and would cost between £43.5 and £65.0 million to implement.

A summary of the cost figures in this section can be found in Table 48.

Table 48: Enhanced Front End Design Cost

Source	Extended front end length (m)	Cost	Cost savings (€million)
(Feist and Faßbender, 2008)	0.13 – 0.2	€400-€600	N/A
(Edwards *et al.*, 2007)	N/A	€220-€350	N/A
(Knight, 2014)	N/A	€220-€350	N/A

Annex 1.5.5 VRU Airbag

Seidl *et al.*, (2017) estimated the cost of a VRU airbag for a car to be €170 based on a windscreen / A-pillar airbag and sensing equipment a cost of 62,000 yen (approx. €517) available to consumers. The OEM cost was calculated to be a third of this price, but to account for the larger airbag sizes that would be required for a HGV this cost was doubled to give a higher estimate of €170-€340.

Annex 2 REVIEW OF RELEVANT REGULATIONS AND STANDARDS

Annex 2.1 Introduction

This Annex reviews the potential regulatory options available for implementing the five safety measures on HGVs with enhanced TFEDs. The Annex identifies the regulations and standards that are most relevant to each of the five safety measures, before evaluating these regulations and standards to understand what changes may potentially be required to ensure these requirements are applicable to HGVs with both traditional and enhanced TFEDs. Finally, any potential regulatory conflicts were identified for the safety measure clustering strategies, alongside also identifying complimentary requirements.

Annex 2.2 Methods

The regulations and standards identified for review include:

- The EU Weights and Dimensions Directives
- The HGV Direct Vision Standard (DVS) star rating scheme
- UNECE Regulation 46 (Devices for Indirect Vision)
- UNECE Regulation 93 (Front Underrun Protection)
- UNECE Regulation 29 (Cab Strength)
- UNECE Regulation 127 (Pedestrian Safety)
- The APROSYS Heavy Vehicle Aggressivity Index (HVAI)

Each of these regulations and standards is reviewed and appraise in the below sections. These sections provide a summary of each regulation or standard, an evaluation of the compatibility of the regulation or standard with enhanced TFEDs and a discussion of the options for the adoption and future development of these regulatory requirements within Directive (EU) 2015/719.

Annex 2.3 Overview of Regulatory Constraints on Vehicle Dimensions

In 1996, Directive 96/53/EC: laying down for certain road vehicles circulating within the community the maximum authorized dimensions in national and international traffic and maximum authorized weights in international traffic (96/53/EC) set out new dimensions for HGVs (UNECE, 1996). Under the directive, the maximum length for an articulated and drawbar HGVs became 16.5 m and 18.75 m respectively. The maximum width was also increased to 2.55 m (2.6 m for refrigerated vehicles). The 12 m limit for rigid vehicles and 4 m height limit remained the same.

Under certain conditions, 96/53/EC allows member states to allow HGV combinations larger than the maximum permitted dimensions in their own country. Two examples of this include Sweden, where it is possible to have a 25.25 m long combination and the UK which does not enforce a 4 m height limit. Instead 4.88 m has become the default height based on existing road infrastructure.

Directive (EU) 2015/719: amending Council Directive 96/53/EC laying down for certain road vehicles circulating within the Community the maximum authorised dimensions in national and international traffic and the maximum authorised weights in international traffic (2015/719) amended 96/53EC on the 5th of May 2015 (UNECE, 2015a). The directive grants exemptions to truck design parameters to allow manufacturers to produce safer HGVs with cleaner, but heavier, alternative powertrains and improved aerodynamics. The directive also amends certain sections of 96/53EC to help encourage the uptake of intermodal transport.

Member States will have the option to restrict the movement of these larger vehicles from certain parts of their road network infrastructure because of the risk to other road users and the limitation of local infrastructure.

In addition to the weights and dimensions, other regulations also have an effect on the maximum length of possible cab extensions.

Regulation 1230/2012: Implementing Regulation (EC) No 661/2009 of the European Parliament and of the Council with regard to type-approval requirements for masses and dimensions of motor vehicles and their trailers and amending Directive 2007/46/EC of the European Parliament and of the Council (Reg 1230/2012) sets out the maximum turning circle requirements for vehicles (UNECE, 2012a).

A vehicle must be able to complete a 360° turn within the boundaries of two concentric circles (5.3 m and 12.5 m radius) without any of the vehicles outermost points extending beyond the outer circle or inner circle. For a semi-trailer combination without rear axle steering, 16.5 m is the maximum length which can be reached without the front corner of the tractor unit leaving the outer circle.

Turning circle is less of an issue for certain types of HGV (Knight, 2014). The majority of rigid HGVs are shorter than the 12 m limit because of the heavy loads they tend to carry (e.g. tippers, concrete mixers etc.). This is also the case for most prime movers in typical 18.75 m rigid drawbar combination which are approximately 10 m (with a 7.825 m trailer). A study by OECD (2011) found 18.75 m rigid drawbar combinations tend to have a narrower swept path than a 16.5 m semi-trailer coupled to a tractor unit.

Regulation 93 specifies the minimum requirements for HGV Front Underrun Protection (FUP) (UNECE, 1994). A vehicle with a FUP device that deformed in the regulatory test by the maximum 400mm could be extended by approximately 450 mm when factoring in UNECE Reg 93 and turning circle requirements (Knight, 2014). In the same investigation Knight identified several existing FUP devices that deformed by 50 mm or less. A FUP of equivalent stiffness could allow up to 800mm under current regulations. For more information on Reg 93 see Annex 2.4.1.

Annex 2.4 HGV Direct Vision Standard (DVS)

Annex 2.4.1 Summary

The HGV Direct Vision Standard (DVS) was originally proposed to measure and score the level of direct vision for various types and models of HGVs operating in London using a five star rating scheme. TfL has set a target of removing the majority of zero star trucks from London by 2020 and having a minimum safety standard of three stars by 2024. In the future, further localised minimum scores could restrict certain HGVs from entering specific areas which have a particularly high density of vulnerable road users.

In 2015, TRL developed a draft Direct Vision protocol based on the findings of previous studies, such as The Primary New Car Assessment Programme (PNCAP) Visibility Protocol and existing vision requirements (Robinson *et al.*, 2016). For more information see Appendix B: Review of existing procedures in the Definition of Direct Vision Standards for Heavy Goods Vehicles (HGVs): Technical Report.

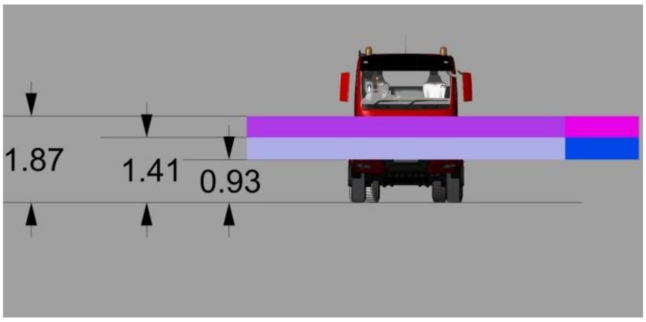
The vision assessment is conducted on a CAD model which is accurate to within ±2 mm of the real vehicle and required set up.

The cab height is determined by several factors. The suspension and tyres must set to the manufacturers recommended levels. The fuel tank must be filled to at least 90% of the manufacturers recommended capacity. The driver’s seat is occupied by a driver with a mass of 68 kg and no additional payload, or ballast, must be added.

The HGV steering wheel centre-point should be adjusted to the nearest point on the 50th percentile steering wheel preference line (preferred steering wheel position of the UK population) to the centre of the steering wheel adjustment range.

Certain design features can cause visual obstructions. If the feature is used regularly, such as a mirror, it must be positioned in its in-use position (the mirrors cannot be stowed away) to allow for a worst case scenario. If the feature is used on a less frequent basis, e.g. windscreen wipers, they must be positioned in their not-in-use position. The passenger seat must be positioned mid-point between the fully forward and backwards position.

Using collision data and anthropometric data, a minimum visible area for the driver was set out for the front and nearside of the vehicle. The two zones were then split in to two layers (creating four sub zones) (see Figure 38). The 0.93 m lower boundary height represents the waist height of a 5th percentile female and the 1.87 m upper boundary height represents the overall height of a 95th percentile male. The 0.3 m offset represents the closest a VRU can walk or cycle alongside the vehicle and is measured from the VRU centre line (centre of chest) and along the width of the shoulder (allowing for a suitable amount of clearance).



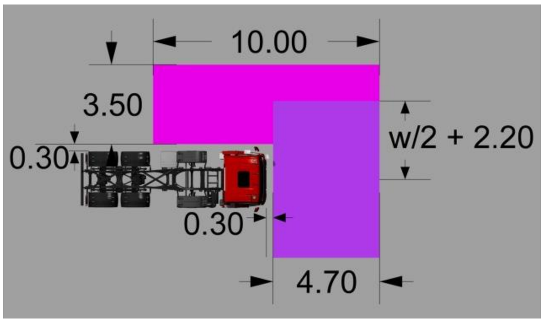


Figure 38: Vision Zone Dimensions (W is width of vehicle) (Robinson *et al.*, 2016)

The zones are marked out by the co-ordinates found in Table 51 measured from the origin of the assessment environment.

Table 49: Vision Zone Dimensions (insert citation)

Vehicle Side	Longitudinal	Lateral	Vertical Lower	Vertical Upper
Front	from 300 mm up to and including 5,000 mm	[-(w/2+2,200)mm to +(w/2+2,200) mm inclusive	from 930 mm inclusive up to and including 1,410 mm	above 1,410 mm up to and including 1,870 mm
Nearside	0 mm to -5,500 mm	(w/2+300) mm to (w/2+3,800) mm inclusive	from 930 mm inclusive up to and including 1,410 mm	above 1,410 mm up to and including 1,870 mm

If the geometry of the vehicle leads to an assessment zone having an offset greater than 0.3 m, the zone shall be adapted to follow the contours of the of the cab to maintain this distance.

A score is calculated by projecting the area which can be seen, by at least one of two eyes of a 50th percentile UK male driver, into the assessment zones then subtracting the visible volume of the assessment zones to determine the blind spot areas (See Figure 39).

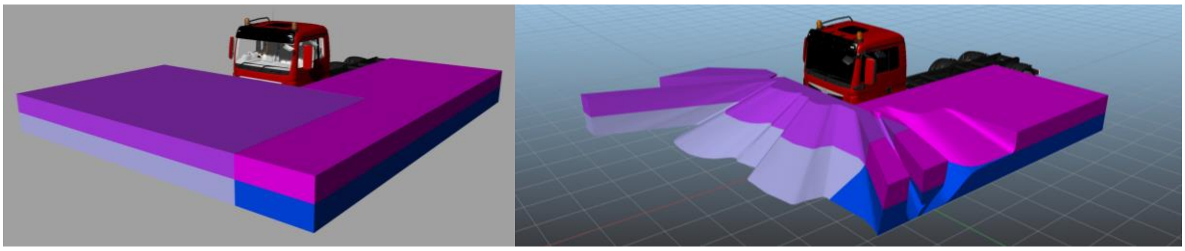


Figure 39: Standard N3G assessment zones before (left) and after the visible volume is subtracted (right) (Robinson *et al.*, 2016)

The visible volume was multiplied by the corresponding weighting for each of the sub zones (Table 50) and added together to produce the overall score.

Table 50: Zone weightings

Front Zone		Nearside Zone	
Front Upper	**Front Lower**	**Nearside Upper**	**Nearside Lower**
11	33	14	42
Front total 44%		Nearside total 56%	

The vehicles are then rated using the ranges found in Table 51

Table 51: Direct Vision score boundaries, table adapted from (Robinson *et al.*, 2016)

Star Rating	Rating Boundaries
0 Stars	≥0 and ≤0.40
1 Star	>0.40 and ≤0.45
2 Stars	>0.45 and ≤0.50
3 Stars	>0.50 and ≤0.55
4 Stars	>0.55 and ≤0.60
5 Stars	>0.60 and ≤1.00

Robinson *et al.* (2016) scored a selection of designs, including a standard N3G and Low Entry Cab to test the method. The Low Entry Cab scored 0.65, the equivalent of five stars.

Loughborough Design School is currently in the process of developing the TRL Direct vision protocol further.

Annex 2.4.2 Compatibility with extended cab designs

The following bullet points summarise some considerations that should be made when considering compatibility with extended front end designs:

- DVS zone dimensions can be adapted to fit non-flat front vehicles
  - If the geometry of the vehicle leads to an assessment zone having an offset greater than 0.3 m, the zone shall be adapted to follow the contours of the of the cab to maintain this distance.
- The zone weightings will still be compatible as these are based on collision landscape
  - Collisions hotspots may eventually move if a new nose (possible additional windows) are introduced on a large scale.
- New cab design may require new/ more specific definitions of front and nearside zones

Annex 2.4.3 Opportunities for future development

The following bullet points summarise some opportunities for further development with the implementation of extended front end designs:

- Define front and nearside zones (when the driver is looking straight forward X^{o} either side of centre line) e.g. the driver is sat in a forward position in a cab with a rounded profile.

Annex 2.5 UNECE Regulation 46 (Devices for Indirect Vision)

Annex 2.5.1 Summary

The purpose of Regulation 46: Uniform provisions concerning the approval of devices for indirect vision and of motor vehicles with regard to the installation of these devices (Reg 46) is to set out a minimum visible area surrounding a vehicle the driver must be able to see with the aid of a combination of indirect vision devices such as mirrors or cameras (UNECE, 2016).

Reg 46 sets out seven main vision requirements (Class I - VII) and installation criteria for M, N and L_1 (with bodywork at least partly enclosing the driver). Out of these seven; Class II (Main rear view), IV (Wide-angle rear view), V (Close-proximity view) and VI (Front-view) are mandatory for HGVs above 7.5 tonnes. The fitment of a Class I (Rear view) mirror is optional and has no set requirements.

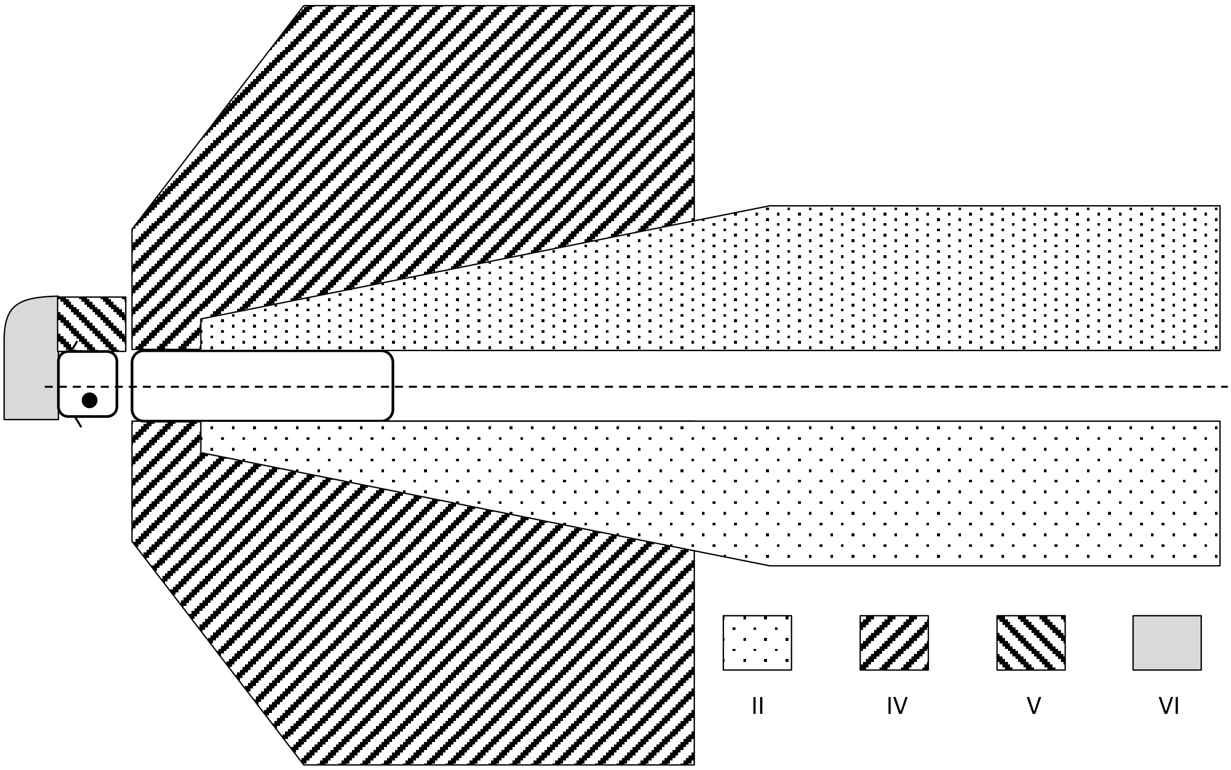


Figure 40: Mandatory HGV mirror classifications and regulated minimum visible areas (UNECE, 2016)

A Class II (Main rear view) mirror is compulsory on both the driver and passenger side of the vehicle. The driver's side class II ground plane starts 1 m from the outermost point of the HGV from a point 4 m back from the drivers ocular points to a minimum horizontal distance of 5 m, measured from the outermost point of the HGV, extending from 30 m behind the drivers ocular points to the horizon (see Figure 40). The passenger side uses the equivalent points and dimensions.

A Class IV mirror is also compulsory on both sides of a HGV cab. The driver's side class IV ground plane starts off 4.5 m from the furthest point of the HGV from appoint 1.5 m back from the drivers ocular points to a minimum horizontal distance of 15 m, measured from the outermost point of the HGV, extending from at least 10 m to 25 m behind the drivers ocular points to the horizon (see Figure 40). The passenger side uses the equivalent points and dimensions.

A Class V mirror is only compulsory of the passenger side of a HGV. The driver's side field of vision provided by a Class V device extends 2 m from the side of the cab as well as 1 m forwards and 1.75 m rearwards of the drivers ocular points (see Figure 40). On the passenger's side the field of vision is larger. The ground plane extends 4.5 m from the cab, 3 m forward and 1.75 m rearwards of the driver's ocular points (see Figure 40). A 2 m radius may be permitted to the front nearside corner. These larger vision requirements do not apply when any part of a class V mirror is below 2.4 m the road surface.

If the appropriate amount of field of vision is provided by a combination of both a Class IV and VI device, a class V device is not required.

The field of vision provided by a Class VI device must make 2 m from the front of the vehicle to the outer most point of the near side of the cab visible to the driver (see Figure 40). A 2 m radius may be permitted to front nearside corner. If the field of vision cannot be fulfilled using a front-view device (mirror) a vision support system can be used instead. The system must be able to detect an object, in the same ground plane, which is 0.5 m high with a diameter of 0.3 m.

If the driver can see a 0.3 m straight line in front of the vehicle from a height of 1.2 m above the road and is positioned between a longitudinal vertical plane parallel to the longitudinal vertical median plane going through the outermost point of the offside of the vehicle and a longitudinal vertical plane parallel to the longitudinal vertical median plane 0.9 m from the outermost point of nearside side of the vehicle, a Class VI device not mandatory.

The distance an indirect vision device can be mounted beyond the external body work must be kept to a minimum to comply with the field of view requirements.

A Camera Monitoring System (CMS) may be used to view a specific area instead of a mirror. For this to happen, the field of view must be, at least the same as its equivalent mirror and meet the minimum requirements set out in this regulation. Reg 46 sets out the magnification, resolution and colour range for camera monitoring systems. A camera Monitoring System must provide a clear and smooth image in a variety of environmental conditions such as sunlight shining directly in to the lens. To reduce blooming, the saturation area of a Class V and VI (the area in which the luminance contrast ratio of a high contrast pattern falls below 2.0) shall not cover more than 15% of the displayed image. To test this, a medium grey test pattern with a minimum contrast ratio of 20 shall be positioned in front of the camera and be evenly lit at an illumination of 3,000 ± 300 lx. A light source emitting of 40 klx, simulating the sun, is then directed at the camera "at an angle between 0.6° and 0.9° with an elevation angle of 10° removed from the optical axis of the sensor". "The source shall have a spectrum D65 ±1,500 K; be homogeneous in space and time within a tolerance of 2 klx and emit minimal infra-red.

There is no minimum number of CMSs on a HGV as long as they meet an equivalent level of vision as the mirror it will replace. However to prevent sensory overload the maximum number of monitors cannot be more than the equivalent number of number of mirrors for which the system replaces.

Dual purpose monitors must display the relevant fields of vision to the driver when the ignition or the vehicle master control switch is switched on (dependant on vehicle) until the vehicle reaches 10 km/h (When travelling forward or backwards). After which the monitor (or a section of the monitor) intended for displaying the Class VI field of vision may be used for other uses such as SATNAV. Non-continuous images need to be clearly separated from each other to avoid confusing the driver. A combined continuous image without clear separation is allowed. The driver must be able to successfully recognise when the system is not functioning.

CMS replacing Class II (and III) mirrors should be activated when the vehicle is opened (vehicle unlocked or door opened), the system must remain operational for at least 120 seconds after the engine has been switched off and a further extended period of time (420 seconds minus the operational time post engine switch off) where the system can reactivated in such a way the driver can see the required field of vision within one second by moving (automatically or manually) any front door of the vehicle. After this time period the system must be able to reactivate in less than seven seconds if a door is opened.

The installation of a monitor should have as smaller impact on driver direct vision as possible. The centre of a monitor should not be below a plane passing through the driver's ocular points and declined 30° below and be roughly in the same direction as the mirror it is replacing.

When installed in their recommended locations, not taking in to account adjustment position, any part of the device or devices which could come into contact with a sphere either 165 mm in diameter, for external components, or 100 mm, for internal components, must have a minimum radius of 2.5 mm.

An indirect vision device shall be positioned that the driver has a clear view of the road to the front, rear and sides of the HGV while sitting in their normal position. To reduce the risk of injury or damage a device must not protrude any further than necessary to achieve the vision requirements for its relevant class.

The driver’s side Class II and IV mirror (or monitor) shall be installed so that the angle between vertical longitudinal median plane of the HGV and the vertical plane passing through the centre of the mirror and through the centre of the straight line 65 mm long which connects the driver's two ocular points does not exceed 55°.

If the lower edge of a Class II to VII mirror is less than 2 m above the ground, when the vehicle is at its maximum laden weight, the mirror cannot extend further than 250 mm beyond the overall width of the vehicle, excluding mirrors.

A class V and VI mirror cannot be installed lower than 2 m above the ground (including after adjustments) when the vehicle is at its maximum laden weight. If the cab height does not permit this, the mirrors or alternative indirect vision devices are not mandatory.

The driver’s side class II mirror must be able to be adjusted from inside the cab while the door is closed. The window may be open.

Obstruction due to body work and its components, such as indirect vision devices, will not be taken in to consideration unless it reduces the field of view of Class II, IV, V and VI devices by more than 10%. The level of obstruction can be tested by placing light sources at the ocular points and examining the amount of reflected light on a the vertical monitoring screen.

Indirect vision devices are required to have two impact tests. The test is conducted using a pendulum capable of swinging about two horizontal axes at right angles to each other. At the end of the pendulum there is a rigid sphere hammer with a 165 ± 1 mm diameter and a 5 mm thick rubber outer layer of Shore A hardness 50. The hammer swings from an angle of 60° measured from the vertical must strike mirrors at the centre of the visible area of the reflecting surface in test 1 and the opposite side in test 2.

If a Class II or IV mirror is fitted, to a vehicle loaded to its maximum mass, above the 2 m minimum height (irrespective of adjustment position), it does not require an impact test. This is also the case for indirect vision device to body work attachments, such as arms or swivel joints, that are mounted less than 2 m above the ground and do not project beyond the overall width of the vehicle; devices that are integrated into the vehicle and whose frontal deflection area is less than 45° measured in relation to the longitudinal median plane of the vehicle and devices protruding less than 100 mm from the outside of the vehicle.

The pendulum shall continue to swing after the impact until the swing angle reaches 20° or 10° for Class II and IV devices. The reflecting surface shall not break during the test. Any fragments must remain glued to the back of the housing (partial separation of 2.5 mm either side of the crack is acceptable) however small splinters are permitted. The reflecting surface must be made from safety glass.

In the case of Camera Monitoring Systems, the hammer must strike the camera on the lens side in test 1 and the opposite side to the lens in test 2. The lens must not break.

Annex 2.5.2 Compatibility with extended cab designs

The following bullet points summarise some considerations that should be made when considering compatibility with extended front end designs:

- The current Reg 46 vision requirements could be compatible with certain HGVs with enhanced front end designs depending on the length of the extension.
- Camera requirements are compatible
- Class V and VI FOV mat may require adjustment to fit certain new cab profiles.
  - If the appropriate amount of field of vision is provided by a combination of both a Class IV and VI device, a class V device is not required.
  - Class VI vision requirements could be compatible with some enhanced front end designs
  - If the Class VI field of vision cannot be fulfilled using a front-view device (mirror) a vision support system can be installed instead. The system must be able to detect an object, in the same ground plane, which is 0.5 m high with a diameter of 0.3 m.
  - If the driver is capable of seeing a straight line 300 mm in front of the vehicle at a height of 1.2 m above the road positioned within the boundaries set in the summary above a Class VI device is not required
  - Body work obstructions of 10% or less to the Class VI FOV are not taken into account. A small extension might not be an issue.
- Class II, IV, Vision requirements could be incompatible with certain rounded cab designs.
  - A driver sat forward and in a central driving position using vision requirements complying with Reg 46 could experience blind spots to the rear
- Compatibility with DVS

Annex 2.5.3 Opportunities for future development

The following bullet points summarise some opportunities for further development with the implementation of extended front end designs:

- Depending on the design of the cab, Class II and IV mirrors may be impractical to install. If this is the case an equivalent Camera Monitoring System could be used instead.
- Class V and VI vision requirements may need to be adapted for designs with larger extensions. CMS could be used to supplement mirrors.
- The positioning and installation of mirrors may have to be adapted to fit new cab designs.
- Incorporating aspects of DVS
  - Direct and indirect vision are tackling the similar issues
  - Can remove the need for mirrors and other indirect vision devices by improving the level of direct vision.

Annex 2.6 UNECE Regulation 93 (Front Underrun Protection)

Annex 2.6.1 Summary

The purpose of UNECE Regulation 93: Agreement concerning the adoption of uniform conditions of approval and reciprocal recognition of approval for motor vehicle equipment and parts (Reg 93) is to set a minimum level of quality for FUPD (Front Underrun Protection Devices) design and installation to N2 (a vehicle designed to transport goods and weighs between 3.5-12 tonnes) and N3 (exceeding 12 tonnes) category HGVs, excluding N2G and N3G (off-road) variants (UNECE, 1994). The tests specified in Reg 93 represent a passenger car (M1 or N1) and HGV experiencing a head to head collision. The FUPD improves the safety of car occupants by absorbing impact energy and preventing the car from sliding underneath the HGV during the impact.

The FUPD must have a minimal cross section height of 100 mm for N2 and 120 mm for N3 vehicles and ground clearance of 400 mm. The outermost surface of the FUP device shall be smooth or horizontally corrugated (heads or rivets or bolts may protrude to a maximum of 10 mm) and have a minimum radius of 2.5 mmm to the edges.

The width of the FUPD shall not exceed the width of the mudguard covering the wheels of the foremost axle. It also cannot be not be more than 100 mm shorter either side than the foremost axle, measured from the outermost points of the tyres (excluding the bulging close to the ground) or 200 mm shorter either side if measured from the outermost points of the access steps to the cab.

The manufacturer has the option of testing their product on vehicle or on a rigid test bench. If tested on a test bench, the device must be installed using the same attachments parts as if it were being fitted to a HGV. If the device is being tested on a vehicle, it must be unladen and set up to the HGV manufacturer’s recommendations.

Points P1 are located 200 mm from the longitudinal planes tangential to the outermost points of the tyres (excluding bulging near to the ground); Points P2 are positioned symmetrically 700 – 1200 mm from the median longitudinal plane (specified by the manufacturer) and Point P3 is in the vertical longitudinal median plane (See Figure 41).

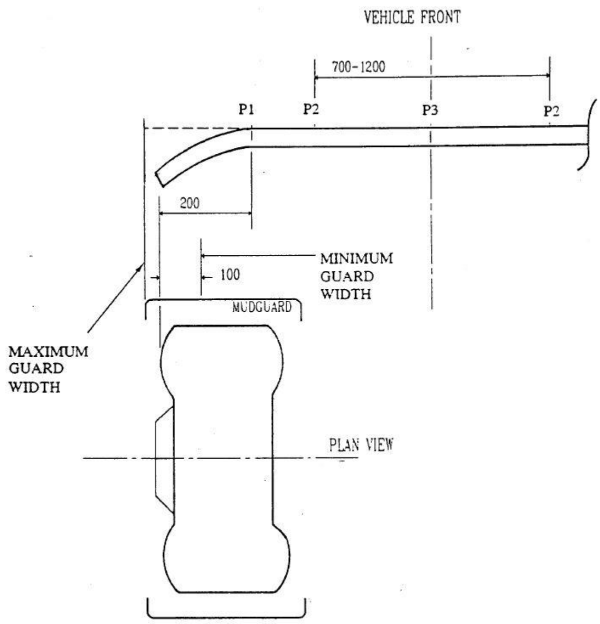


Figure 41: plan view of Reg 93 FUPD dimensions and impact points (UNECE, 1994)

A horizontal force equivalent to 50% of the maximum weight of the vehicle (but not exceeding $80x10^3$ N) and 100% of the maximum weight of the vehicle type but not exceeding 160x103 N) is applied successively to both points P1 and P2 respectively for a minimum of 0.2 seconds. If the device develops a reduced cross sectional area between the two P2 positions, then an equivalent force to the points P1 shall be applied to Point

P3. The forces shall be applied by a ram to the centre of points P1, P2 and P3. The contact surface will be a maximum of 200 mm high by 400 mm wide with a radius of 5 ± 1 mm at the vertical edges

The tests loads cannot be applied to the FUPD any higher than 445 mm from the ground. During the test, the rearwards deformation measured from the foremost part of the vehicle to the front of the FUPD when the test forces are applied cannot exceed 400 mm (see Figure 42) and the maximum ground clearance, measured from to the bottom of the FUPD, between the two P1 points cannot exceed 450 mm.

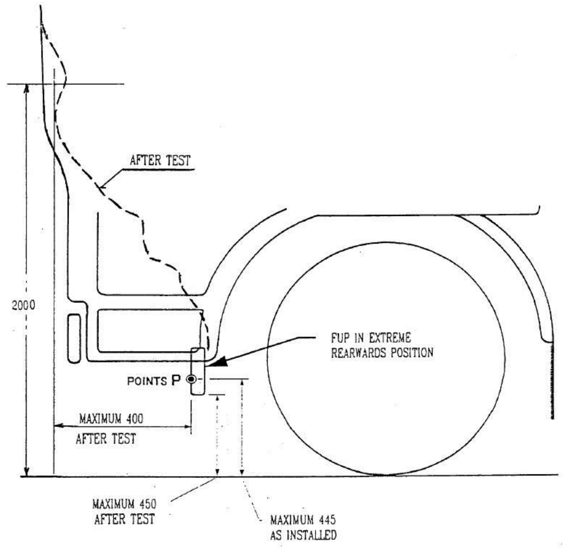


Figure 42: Pre and post-test deformation (UNECE, 1994)

Annex 2.6.2 Compatibility with extended cab designs

The following bullet points summarise some considerations that should be made when considering compatibility with extended front end designs:

- A vehicle which is fitted with a FUP that deforms by the maximum 400 mm in a regulatory test could be extended by approximately 450 mm.
- Study showed the several designs had an appropriate level of stiffness (50 mm deformation) to allow an enhanced front of approximately 800 mm
  - Could be as much as 850 mm for a straight FUP fitted to a vehicle where installing the additional length did not place any 'stiff structures' forward of the position equivalent to the front of a standard length vehicle.
  - To achieve the longer length the devices would need to be stiffer (especially at the P1 points) and heavier (Knight, 2014).
- No curved FUPD tests
- No FUPD test for VRUs

Annex 2.6.3 Opportunities for future development

The following bullet points summarise some opportunities for further development with the implementation of extended front end designs:

- Depending on cab design a curved underrun may have to be developed.
- New method for straight FUP in extended nose
- New method for testing to test curved FUP devices is required
  - Impacted by a mobile progressive deformable barrier

Annex 2.7 UNECE Regulation 29 (Cab Strength)

Annex 2.7.1 Summary

ECE Regulation 29: Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants of the cab of a commercial vehicle (Reg 29) ensures a minimum level of HGV cab strength (including cab to chassis) and protection for its occupant in the event of a roll over or cab to rear of trailer impact (UNECE, 2012b).

The manufacturer may use up to three cabs during the testing process. Both parts of the third test must be performed on the same cab. None of the tests need to be carried out if the manufacturers can provide the required evidence through computer simulation or by other methods.

After each of the tests, the cab of the vehicle shall provide a survival space allowing accommodation of the manikin, defined in the report (a fiftieth percentile Hybrid II or III male dummy, with or without measuring instrumentation may be used instead if the preferred option is not available), when it is seated and in its median position. No contact with should be made between the test manikin and non-resilient parts with a Shore-Hardness of 50 or more, excluding parts which can be moved away without any tools from the dummy by using a force of less than 100 N.

The components securing the cab to the chassis frame may be distorted or broken during the tests provided the cab does not become detached form the chassis frame. The cab shall have a steering mechanism, steering wheel, instrument-panel installed as well as both driver and passenger seats. The steering wheel and the seating position shall be adjusted to their manufacturers recommended positions. The cab must be mounted to a vehicle for the frontal impact test and to a vehicle or separate from a for the pillar and roof tests.

The front impact test is only conducted on cab-over HGVs and involves striking the front of the cab with a rectangular steel impactor which is 2500 mm wide by 800 mm high (see b and h in Figure 43) and has a minimum mass of 1500 kg. The edges to the impactor must have a radius of 10 mm± 5 mm. The impactor assembly shall be freely suspended from its supporting structure by two beams spaced a minimum of 1,000 mm apart (see f in figure x) and 3500 mm in length when measured from the axis of suspension to the centre of the impactor (see L in Figure 43).
The impactor is set up to impact the foremost position of the vehicle with an impact energy of 55 kJ (for N2 and N3 vehicles which have a gross vehicle mass of more than 7.5 tonnes) when in the vertical position. Its centre of gravity should be c=50 +5/ - 0 mm below the R point of the driver's seat and in the median longitudinal plane of the vehicle.

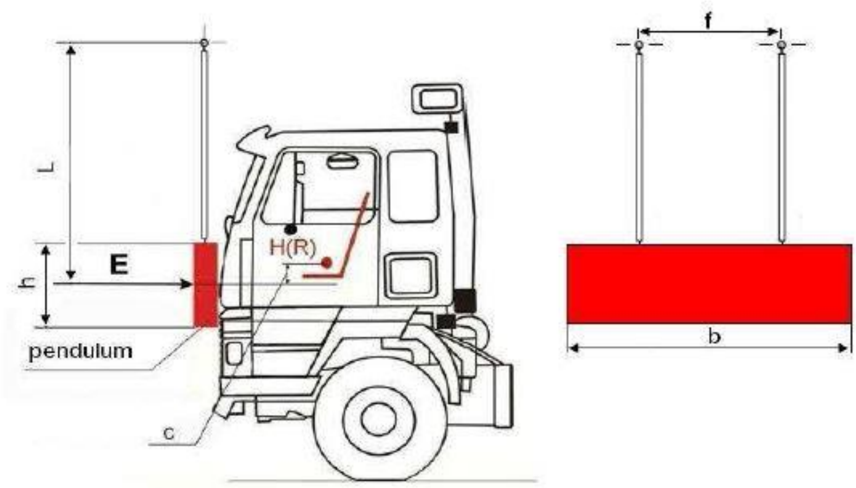


Figure 43: Front impact test diagram (UNECE, 2012b)

The Front Pillar Test is conducted using a rigid cylindrical impactor with a diameter (see d in figure x) of 600 ± 50 mm, a minimum length (see b in Figure 44) of 2500 mm and mass of 1000 kg. The edges must have a minimum radius of 1.5 mm. The impactor assembly uses the same dimensions and measurement points as the construction used in front impact test.

The impactor will strike the foremost part of the cab when it is in its vertical position with impact energy of 29.4 kJ and be positioned so Its median longitudinal line is horizontal and perpendicular to the median longitudinal vertical plane of the cab; the centre of gravity for the impactor is midway up the windscreen frame (when measured along the median longitudinal vertical plane of the cab) and Its centre of gravity is in the median longitudinal plane of the cab;

The length of the cylinder must be equally distributed over the width of the HGV and overlapping the full width of both A-pillars.

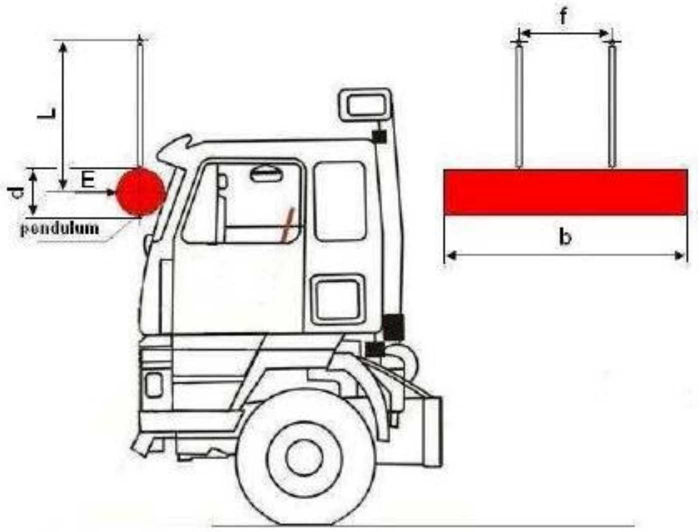


Figure 44: Front pillar test diagram (UNECE, 2012b)

Roof Strength Testing is split into two tests; the dynamic pre-loading of vehicles and the roof test (see P_1 and P_2 respectively in Figure 45).

The impactor used in the first test is flat, rectangular and has a minimum mass of 1500 kg. At the time of impact, the striking face of the impactor should be at an angle of 20° to the median longitudinal plane of the cab. This can be done by tilting the cab or impactor.

The median longitudinal line of the impactor is horizontal and parallel to the median longitudinal plane of the cab. The striking face of the impactor should cover the entire length of the top side of the cab with none of its edges coming in contact with the cab. The minimum impact energy shall be 17.6 kJ.

The Roof strength test (see P_2 in Figure 45) loading device is rectangular and made of steel. It is large enough that when positioned for the test, the cab will not come in contact with its edges. The device shall be so positioned that, during the test; It is parallel to the X-Y plane of the chassis; It moves parallel to the vertical axis of the chassis and Its loading face covers the whole area of the cab roof.

The static load applied by the device to the roof of the cab should be equivalent to the maximum mass authorised for the front axle(s) of the vehicle, but not exceeding 98 kN).

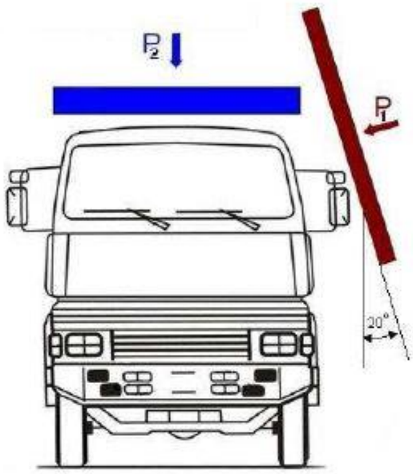


Figure 45: Roof strength testing (UNECE, 2012b)

Annex 2.7.2 Compatibility with extended cab designs

The following bullet points summarise some considerations that should be made when considering compatibility with extended front end designs:

- Aspects of Reg 29 are compatible with enhanced front end designs
- Front Impact test is not conducted on non-flat fronted HGVs
- Pillar and roof strength tests are compatible with enhanced front ends

Annex 2.7.3 Opportunities for future development

The following bullet points summarise some opportunities for further development with the implementation of extended front end designs:

- Suggest car or mobile progressive deformable barrier to replace front impact test

Annex 2.8 UNECE Regulation 127 (Pedestrian Safety)

Annex 2.8.1 Summary

Regulation 127: Uniform provisions concerning the approval of motor vehicles with regard to their pedestrian safety performance (Reg 127) sets out a minimum level of pedestrian safety performance for the majority of M1 (below 2500 kg) and N1 vehicles (UNECE, 2015b). This regulation does not apply to N1 derived M1 vehicles or N1 and M1 vehicles where the driver position (R point) is either forward of the front axle or 1100mm behind the front axle centreline.

The regulation is split into two mains sections; the headform and leg form test.

The head and legform test involves firing a plastic impactor, representative of the body part, at a test zone marked out as a grid, split in to 100 mm x 100 mm squares, on to the bonnet of a vehicle. The parameter of the test zone is defined by locating key surfaces or edges common to most light vehicles such as the Wrap around Distance (WAD).

The adult headform test are is determined by a WAD of 1700 mm or a 82.5 mm line rearward of the bonnet leading edge reference line (whichever is most rearwards), by a WAD 2100 mm or a 82.5 mm line forward of the bonnet rear reference line (whichever is most forward) and a 82.5 mm line inside the side reference line. The child headform test area uses the same edges as markers and side measurements but is defined by the WAD 1000 and 1700.

In tests using both Child and adult headforms, the HIC value cannot be higher than 1000 for two thirds of the bonnet top test area (HIC1000 zone) and 1700 (HIC1700 zone") for the remaining area. In a child headform impact test the HIC 1000 zone must make up a minimum of half the child headform test area. The second half cannot exceed 1700. If there is only a child test area (small bonnet) then the same figures shall be used. The manufacturer of the vehicle must specify these zones prior to the test.

A minimum of nine child headform impact tests are required to happen at locations which are predicted to be cause the most amount of injury (three tests each to the middle and the outer thirds of the child/small adult bonnet top test areas). The headform must impact the test vehicle at 9.7 m/s ± 0.2 m/s at an angle of 50° ± 2° to the horizontal. The direction of impact of tests, to the front structure, shall be downward and rearward. The Adult headform test uses a similar format however the impacts must occur in the middle and the outer thirds of the adult bonnet top test areas at an angle of 65° ± 2° to the horizontal.

The Leg form test is also split into two tests (upper and lower).

For vehicles with a lower bumper height, at the test position, of less than 425 mm, the lower leg form test must be performed. For vehicles with a lower bumper height greater than, or equal to, 425 mm and less than 500 mm the manufacturer has a choice between either test. For vehicles with a lower bumper height greater than, or equal to, 500 mm the upper leg form test must be performed.

During the lower legform test the maximum dynamic medial collateral ligament elongation at the knee and the maximum dynamic anterior cruciate ligament and posterior cruciate ligament elongation cannot exceed 22 mm and 13 mm respectively. The maximum value of dynamic bending moments at the tibia cannot be higher than 340 Nm.

In the upper leg to bumper test, the instantaneous sum of the impact forces, with respect to time, and the bending moment on the test impactor shall not exceed 7.5 kN and 380 Nm respectively.

At least three lower legform to bumper tests must be carried out at locations which are predicted to be cause the most amount of injury (one each to the middle and the outer thirds of the bumper). The tests shall be performed on different types of structure. The impactor is made of materials which represent flesh and skin, flexible long bone segments and has a total mass of 13.2 kg ± 0.4 kg. The impact velocity of the impactor when striking the bumper shall be 11.1 m/s ± 0.2 m/s.

The upper legform is a rigid and covered in foam (at the impact side) and 350 mm ± 5 mm long. The total mass of the impactor (including those propulsion and guidance components) is 9.5 kg ± 0.1 kg. It is fired at similar locations at the same speed.

Annex 2.8.2 Compatibility with extended cab designs

The following bullet points summarise some considerations that should be made when considering compatibility with extended front end designs:

- Reg 127 is not compatible with HGVs
- Reg 127/EuroNCAP HIC values could be used
- Impact speeds not compatible with typical HGV/VRU collisions
- Test zones not compatible with HGVs (flat fronted nose as there will be no WAD)
- Test zones for enhanced front end design may have to be wrapped around cab profile (how will this effect impact angles)

Annex 2.8.3 Opportunities for future development

The following bullet points summarise some opportunities for further development with the implementation of extended front end designs:

- Develop method for marking up head and leg test zones on HGVs for a variety of different shaped extensions.
- Define head and leg form impact requirements for a variety of different shaped extensions.

Annex 2.9 APROSYS Heavy Vehicle Aggressivity Index (HVAI)

Annex 2.9.1 Summary

The APROSYS Heavy Vehicle Aggressivity Index (HVAI) assesses three aspects of HGV design; how VRUs interact with the vehicle structure during an impact (Structural Index), the risk of the vehicle running over a VRU (Run over Index) and the vehicles ability to avoid accidents by providing the driver with a sufficient field of view and through the use of active safety systems (Active Index) (Smith, 2008). This section of the report will focus on the secondary passive aspects of this project; the Structural and Run over Index.

The aim of Structural Index was to develop a test procedure to assess the structural behaviour of the vehicle during the primary impact similar to Reg 127 (Smith, 2008;UNECE, 2015b). The protocol splits the front of the vehicle into an adult and child zone, based on where the head of the pedestrian is likely to hit (see Figure 46) (Smith, 2008). To compensate for changes in ride height during deliveries, the upper boundary of the adult zone and lower boundary of the child zone are defined by when the vehicle is at its minimum ride height (1.849 m) and maximum ride height (1.114 m) respectively.

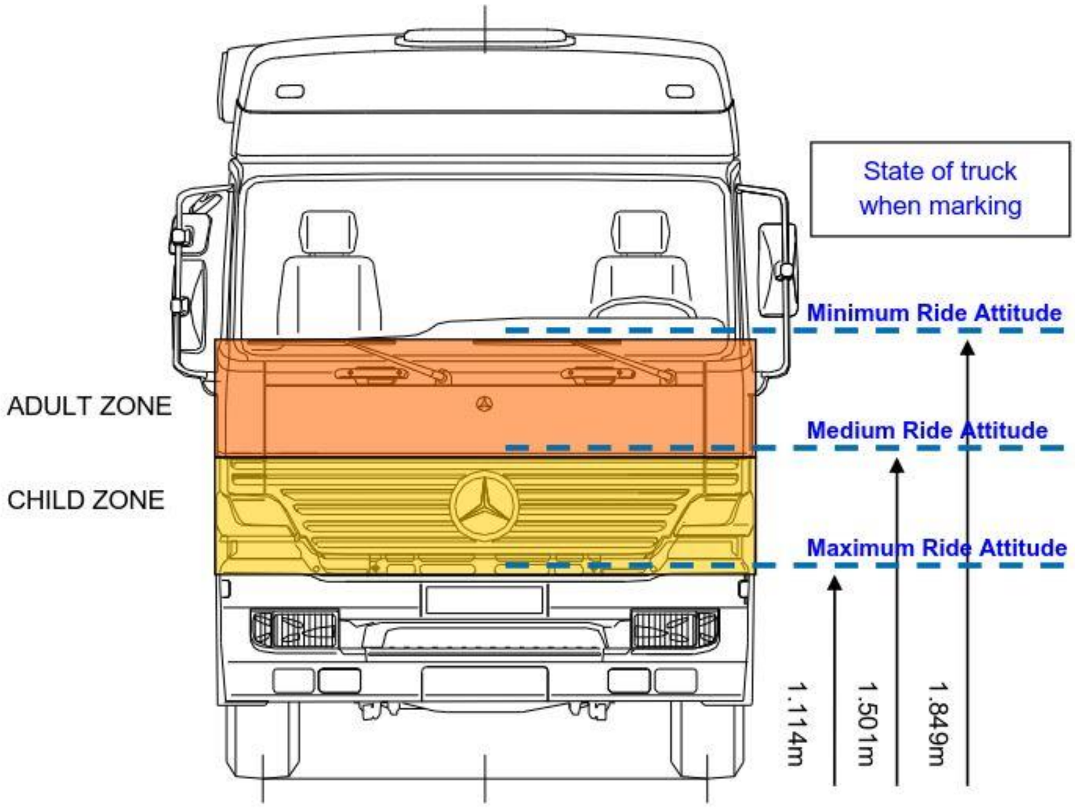


Figure 46: Adult and child zones marking based on vehicle ride height (Smith, 2008)

The adult and child zones are divided in to six areas (See Figure 47), and then sub-dived in to quarters. A point must be selected from each of the twelve sub zones (e.g. A1 or C4) and is chosen based on which would cause the most severe injury to a pedestrian.

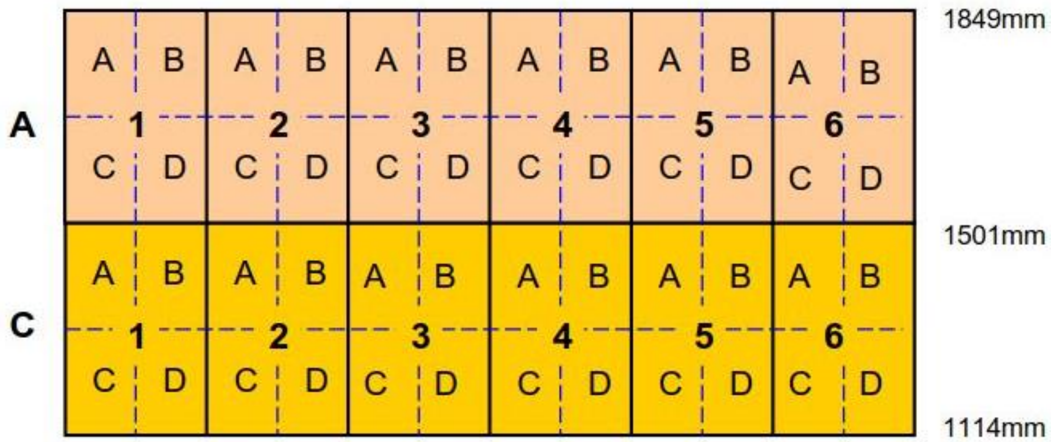


Figure 47: Impact point grid (Smith, 2008)

The vehicle manufacturer can request up to three further tests (one per sub zone) (see highlighted locations in (Smith, 2008)) in addition to the mandatory twelve. The headform is fired at the test vehicle horizontally and at a speed of 11.1± 0.2 m/s

The 15 ms Head Injury Criteria (HIC_{15}) is used to determine an overall score (Smith, 2008). If there sub zone has a HIC value less than 1000 it will score two points (green), if the HIC value is more than 1000 but less than 1350 it will score one (Yellow) and if the HIC value is more than 1350 it will score zero (Red). If an extra point is used (e.g. two on A4) additional weighting is given to the sub zone.

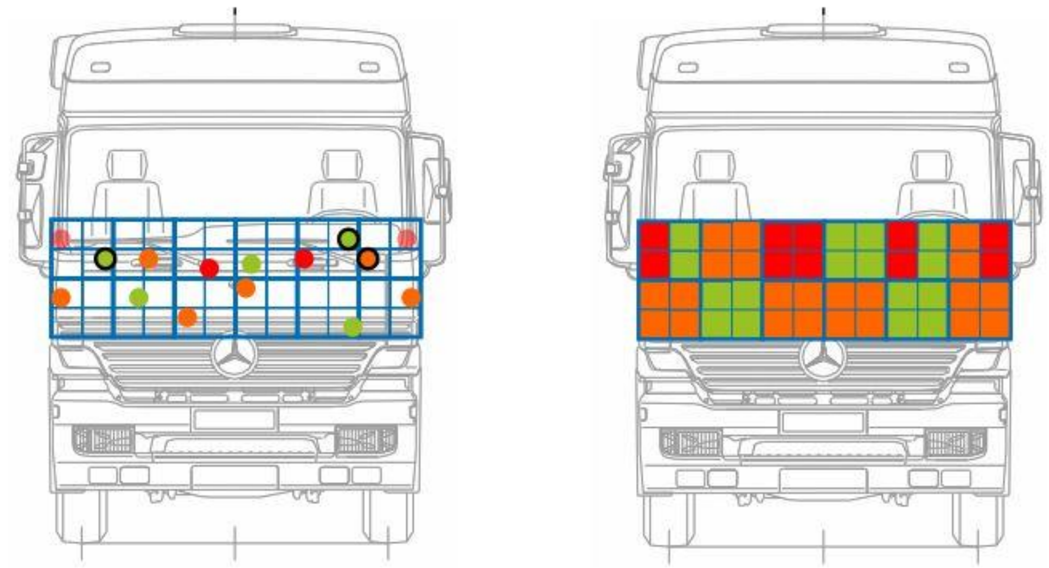


Figure 48: An example diagram of test locations (left) and scoring (right) (Smith, 2008)

The Run over Index assesses a vehicle design by the likelihood of it preventing a VRU from being run over. The aim of the project was to develop a test protocol which could provide a quantitative value of this, taking in to account the wide range of possible HGV configurations. To achieve this, key accident scenarios and impact locations were identified from a literature and accident data review (see Figure 49).

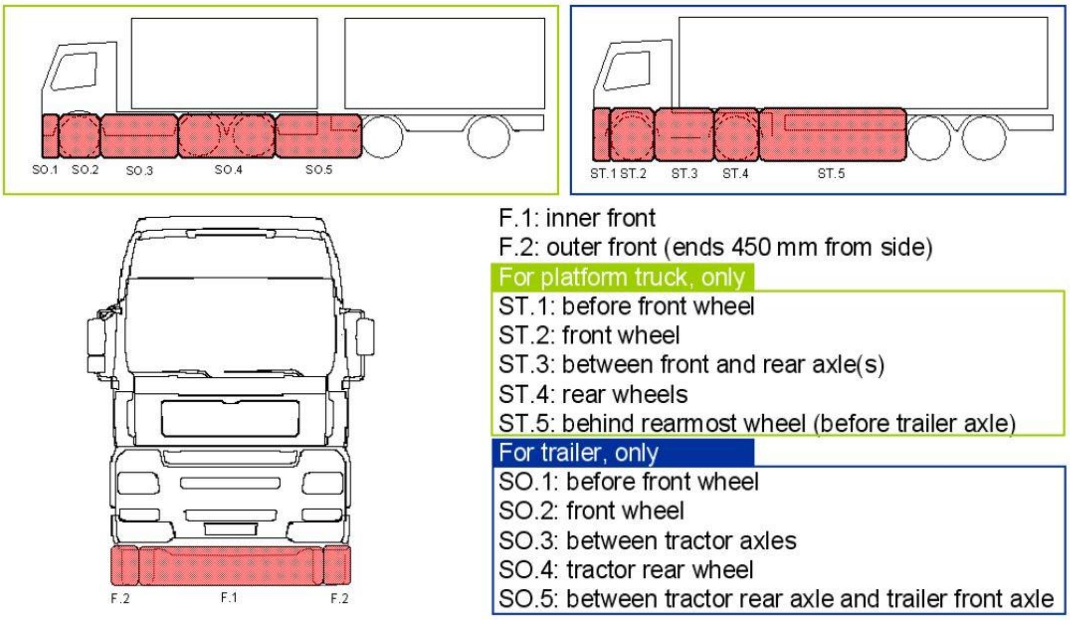


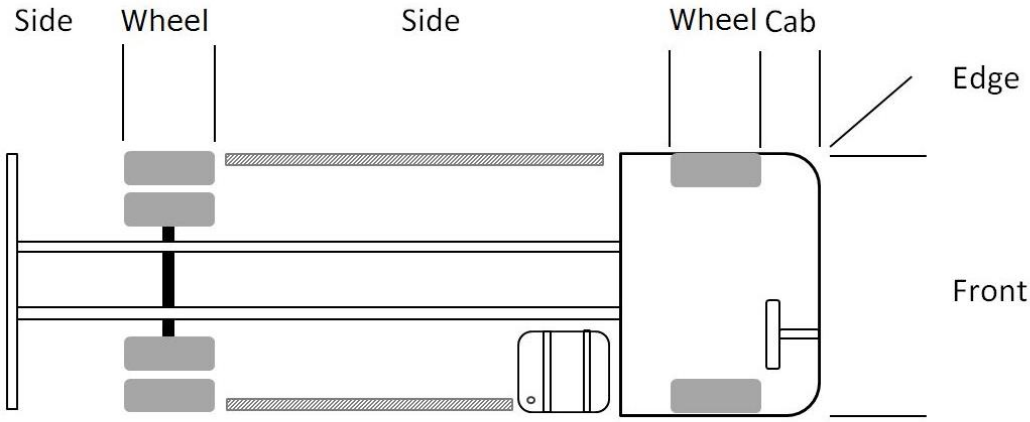
Figure 49: Run over Index defined impact areas (Smith, 2008)

The accident scenarios were linked to their corresponding impact locations and arranged in a matrix of required test simulations (see Table 52). In total 21 possible simulations were recommended.

Table 52: Run over simulation assessment matrix. Table adapted from Smith (2008).

No.	Impact location	Accident Scenario	Orientation of VRU
1	F.1	HGV turning vs pedestrian	45°
2	F.2		45°
3	SO.1/ST.1		0°
4	SO.2/ST.2		0°
5	SO.3/ST.3		0°
6	SO.4/ST.4		0°
7	SO.5/ST.5		0°
8	F.1	HGV turning vs cyclist	45°
9	F.2		45°
10	SO.1/ST.1		45°
11	SO.2/ST.2		45°
12	F.2		0°
13	SO.1/ST.1		0°
14	SO.2/ST.2		0°
15	SO.3/ST.3		0°
16	SO.4/ST.4		0°
17	SO.5/ST.5		0°
18	F.1	Forward driving HGV vs pedestrian	90°
19	F.2		90°
20	F.1	Forward driving HGV vs cyclist	90°
21	F.2		90°

The sub areas set out in Figure 49 were then translated in to the main areas displayed in Figure 50. Each main area was given a weighting based on the likeliness of being involved in a real world accident. For a main area to pass, each sub section must demonstrate run over is prevented.



Sub area	Forward Driving		Turning				
	Front	Edge	Front	Edge	Cabin	Wheel	Side
F.1	✓		✓				
F.2	✓	✓	✓	✓			
SO.1/ST.1				✓	✓		
SO.2/ST.2						✓	
SO.3/ST.3							✓
SO.4/ST.4						✓	
SO.5/ST.5							✓

Figure 50: Main and sub impact areas on an example vehicle. Adapted from Smith (2008)

During the simulations, the VRU is run over if one of the body regions highlighted red in Figure 51 comes in contact with one of the HGV wheels or if the centre of gravity of the VRUs head or hip falls within the defined zones.

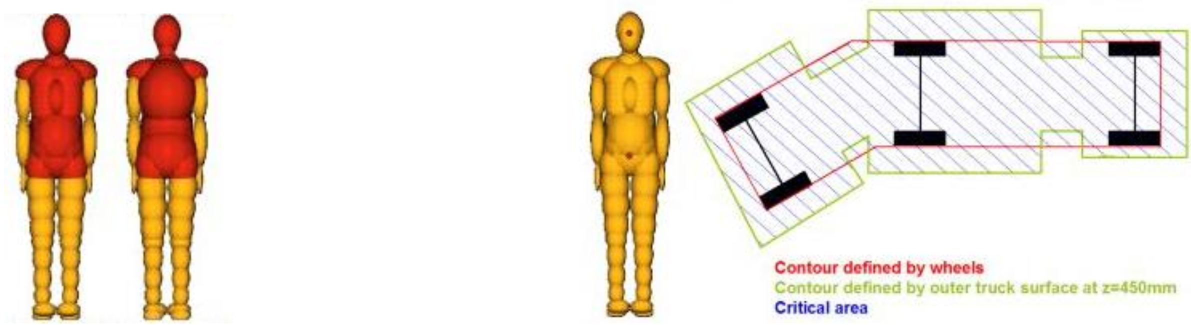


Figure 51: Body regions that must not come in to contact with the wheels (Left) and Critical zones (Right) (Smith, 2008)

If the VRU is not run over, there are three potential outcomes from the impact; Fixing, Isolating and moving away. Fixing refers to when the VRU is not run over and none of the red body regions are involved in a secondary impact, Isolating refers to when the VRU is not run over however red body regions are involved in a secondary impact and moving away refers to when the VRU is not run over and is deflected away from the HGV during the primary impact. Each of the three outcomes has a different level of risk and resulting risk factor, fixing has the lowest (risk factor of 1) as risk as the VRU is not pushed to the ground and Moving away has the same level of risk to Isolating (risk factor of 0.7) due to the uncertainty of the direction and speed of deflection.

Based on the findings of the project literature and accident data the accident scenarios were given the following weightings found in Figure 52.

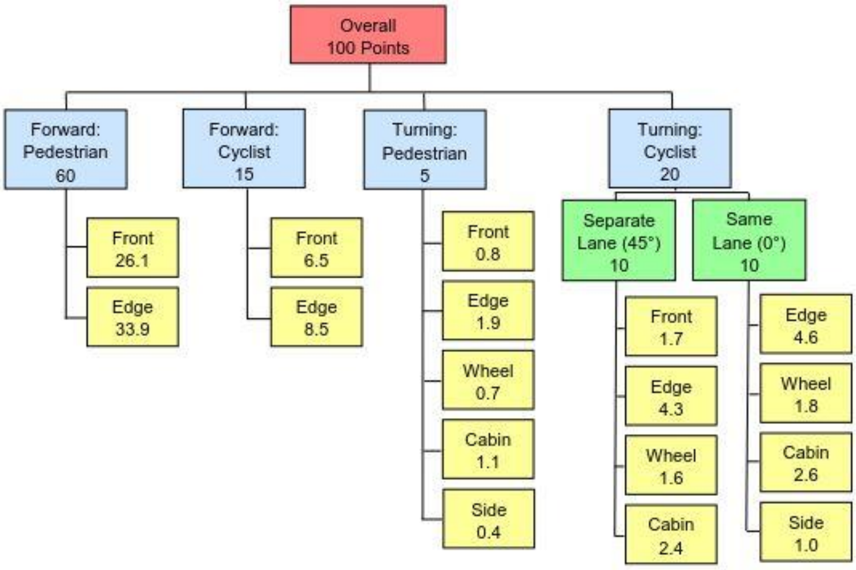


Figure 52: Weighting factor for each accident scenario (Smith, 2008)

The run over (whether the VRU was run over or not) and injury risk data is compiled in a spreadsheet and given a score between zero to ten. The points for each impact scenario and location are then multiplied by an average factor. The average factor is the average of the risk factor of an area if more than two sub areas are involved and achieve different levels of protection, e.g. if one sub area assigned fixing (1) and the other is assigned moving away (0.7), the resulting average would be 0.85. Further information on structural and run over index can be found in their respective technical paper AP-SP21-0090 and AP-SP21-0091

Annex 2.9.2 Compatibility with extended cab designs

The following bullet points summarise some considerations that should be made when considering compatibility with extended front end designs:

- Structural Index is compatible with HGVs
- Structural Index is not compatible with enhanced HGVs
- Run over Index is compatible with HGVs
- Run over Index is compatible with enhanced HGVs.

Annex 2.9.3 Opportunities for future development

The following bullet points summarise some opportunities for further development with the implementation of extended front end designs:

Structural Index

- Comparison of HVAI and (Yamazaki and Ramli, 2013) both recommended similar test zone and airbag installation heights.
  - HVAI test zone 1.114 m to 1.849 m
  - (Yamazaki and Ramli, 2013) Child airbag height 0.8 to 1.2 m and adult airbag height 1.4 to 1.6 m.
- Reg 127 and HVAI recommend similar headform impact speeds
  - Reg 127 (9.7 m/s ± 0.2 m/s)
  - HVAI (11.1± 0.2 m/s)
- HVAI used 11.1± 0.2 m/s as accident data available at the time showed approximately 50% of fatalities occur at impact speeds up to 40-45 km/h.
- TFED target population research shows that interaction speeds are in fact much lower (Annex 1.3)
  - VRUs
    - VRU average walking speed approximately 5.2 km/h (Gates *et al.*, 2006)

  - Cyclists
    - After analysing GIDAS accident data, Schreck and Seiniger reported HGV speed was less than 30 km/h (8.33 m/s) in 90% of collisions and the speed of the cyclist was less than 20 km/h (5.5 m/s) in 85% of collisions (Robinson *et al.*, 2016).
- Suggest requirements for level 1 pedestrian impact protection (low speed manoeuvres)
  - Headform impact speed approximately 5 m/s and a HIC value less than 1000 based on HVAI
- Suggest requirements for level 2 pedestrian impact protection (in line with HVAI and Reg 127).
  - Headform impact speed 11.1± 0.2 m/s and a HIC value less than 1000 based on HVAI

Run over Index

- Redefine the cab, edge and front areas to meet new cab profiles.

Annex 3 OVERVIEW OF ENHANCED TRUCK FRONT END DESIGNS

Annex 3.1 Introduction

This Annex provides a state-of-the-art overview of exemplar and conceptual enhanced truck front end designs (TFEDs), and the available supporting technologies, to provide an overview of the current and potential future technological capabilities of European style, cab-over-engine, HGVs. This Annex will therefore be used to ensure that the regulatory options proposed within this report are deemed technologically feasible by the industry, whilst providing supplementary data from manufacturers on the effectiveness and costs of the solutions from sources that may not otherwise be included via traditional literature review techniques.

Annex 3.2 Methods

Ten highly relevant case studies were selected for this Annex to ensure the technological solutions underpinning each concept encompassed all five safety measures investigated by this project. These cases were reviewed to establish the technological capabilities of each solution, determine what safety measures the solutions could potentially address and provide a top-level appraisal of the benefits and limitations of implementation. In addition, any information relating to the costs or effectiveness of these solutions was also abstracted from these sources. It must be noted, however, that the information from a number of these case studies was either from previously reviewed research sources or from manufacturer marketing material.

Annex 3.3 Summary of Selected Case Studies

Ten case studies were selected to represent the broad range of technological capabilities currently available to the HGV industry. A summary of these case studies, and the safety measures that they provide a technological solution to (see Section 2.3 for further detail on safety measures), may be seen in Table 53. These are ordered chronologically, according to concept launch date rather than intended date of concept operation, whilst an explanation of the safety measure codes is provide below the Table.

Table 53: Safety measures for selected TFED case studies

Case Study	DIR	CAM	DET	VIP	FUP	VAB	Active
Scania Crash Zone Concept				✓	✓		
APROSYS				✓		✓	
Fuso Concept HGV	✓	✓	✓	✓			
Volvo Trucks 2020 Vision Concept	✓	✓		✓			
FKA Concept	✓			✓	✓		
MAN Concept S		✓		✓			
Volvo V40						✓	✓
Low Entry Cab HGV Variants	✓	✓	✓	✓			✓
Iveco Z Truck	✓	✓	✓				
Camera and Detection Systems		✓	✓				✓

Of the ten case studies reviewed within this project, five included cabs with direct vision [DIR] solutions, whilst seven had indirect vision devices fitted (six used cameras [CAM] and four used sensor-based detection systems [DET]). Seven vehicles featured enhanced TFEDs for VRU impact protection [VIP], whilst two mentioned the use of front underrun protection devices [FUP], two looked at VRU airbags [VAB] and three featured at least one form of primary active safety solution [Active].

It should also be noted that there are less rigid truck case studies included in this Annex if compared to articulated tractor units. This is primarily due to the typical configuration of a rigid truck (e.g. box, tipper, cement mixer, etc.) rarely achieving current 12 m rigid truck length limits. This is primarily due to rigid trucks reaching maximum gross weight limits before lengths or cubic volumes become an issue or a requirement for greater manoeuvrability. Despite this, a number of rigid trucks case studies were included in this review as they have implemented several solutions that are applicable to the five safety measures reviewed by this project.

All vehicles had at least two safety measures implemented in their design and all safety measures had at least two vehicles demonstrating a relevant solution. This demonstrates that the automotive industry has, to a degree, given the technology solutions contained within this report for each safety measure some consideration already.

Annex 3.4 Scania Crash Zone Concept (Case Study 1)

Annex 3.4.1 Key safety measures

The two key safety measures adopted by the Scania Crash Zone Concept are:

- VRU Impact Protection [VIP] (Passive Safety)
- Front Underrun Protection [FUP] (Passive Safety)

Annex 3.4.2 Concept overview

The Scania Crash Zone concept was launched alongside the 2003 Scania Road Safety Conference and was developed in collaboration with Volvo 3P, Finnveden Metal Structures, Outokumpu Stainless, SAPA, and Linköping University (Nilsson and Forsberg, 2006). It incorporated lessons learnt from the Vehicle Crash COMPATibility (VC-COMPAT) test series which discovered existing HGV Front Underrun Protection (FUP) devices could prevent more cars from underrunning a HGV if their design was further developed (Gwehenberger *et al.*, 2004).

The model shown in Figure 53 was created mainly as a styling exercise to gauge the reaction of the public to the manufacturer combining an improved energy-absorbing FUP system with Scania styling (Scania, 2003). However another section of the overall programme resulted to three FUP designs which behave like a rigid FUP for relative velocities up to 56 km/h and Energy Absorbing Front Underrun Protection (EA-FUP) devices for the absorbance of kinetic energy above 56 km/h in frontal impacts (Nilsson and Forsberg, 2006). Further requirements included a maximum deceleration of 30g in the first 100 ms and a total maximum deceleration of 40g.

Figure 53: Scania Crash Zone Concept full scale model (Scania, 2017)

The Crash Zone Concept had 800 mm of crumple zone for absorbing the impact force in the event of impacting a car (Commercial Motor Archive, 2009a;Commercial Motor Archive, 2009b). This was comprised of a 600 mm deformable bonnet and a further 200 mm frontal underrun protection area and front bumper found on a conventional HGV. In addition to the primary lower impact structure, the concept had a large vertical grille which acted as an upper secondary crumple zone intended for improved energy absorption in cab to rear of trailer collisions. Importantly, this upper impact zone also had a 100 mm thick outer layer incorporated into the design to provide "survivable protection" for interactions with cyclists and pedestrians at speeds of up to 40 km/h.

The FUP device was predicted to increase the survivable collision speed from 56 km/h to 90 km/h (Nilsson and Forsberg, 2006). This could help prevent up to 900 HGV-to-car fatalities related to frontal collisions per year at the time of launch (Commercial Motor Archive, 2009a).

This early enhanced front end design had several limitations, for example the longer nose meant it had an increased turning circle, reduced ground clearance and approach angle compared to a conventional cab-over-engine design (Commercial Motor Archive, 2009a). Furthermore the additional structure would have added 250-350 kg to the gross train weight and, unlike the majority of the case studies reviewed in this section, the nose on this HGV also reduced the level of forward visibility.

Annex 3.5 APROSYS Nose Cone Truck (Case Study 2)

Annex 3.5.1 Key safety measures

The two key safety measures adopted by the APROSYS Nose Cone Truck are:

- VRU Impact Protection [VIP] (Passive Safety)
- Vulnerable Road User Airbag [VAB] (Passive Safety)

Annex 3.5.2 Concept overview

The Advanced PROtection SYStems (APROSYS) project was a large investigation carried out between 2004 and 2010 that reviewed the scenarios underpinning road collisions and the crashworthiness of vehicles (Department for Transport, 2011). The overall aim of the project was to develop systems to reduce the number of injuries and fatalities on the roads. The project was split based on vehicle type, with perhaps the most important work package being APROSYS SP2: heavy truck accidents concerning accidents with pedestrians and accidents with passenger cars (Gugler, 2009).

One of the key outcomes of SP2 was the development of the Heavy Vehicle Aggressivity Index (HVAI) (Smith, 2008). As part of the HVAI, a wide range of passive and active design features were evaluated to assess their ability to improve the safety of VRUs in three key aspects of HGV vs VRU related collisions: the risk of the HGV running over the VRU (run over index), the risk of injuries occurring from the primary impact (structural index) and the driver field of vision (both direct and indirect) in the immediate area surrounding the vehicle (active index) (Bovenkerk and Fassbender, 2006). In addition to investigating potential design solutions, SP2 also proposed a series of test protocols to assess a vehicles performance in these three key areas (Smith, 2008). These included a method of identifying whether a pedestrian has been run over or not and scoring the HGVs design at preventing this (run over index), A method of marking out and scoring the severity of VRU head impacts during the primary collision using a grid system (structural index) and a scoring scheme to determine the drivers field of view from the cab (active index). The HVAI run over and structural index are discussed in more detail in Annex 2.8.1.

Of the many solutions assessed for their feasibility, two main solutions were selected to be developed further; the nose cone and Safety Bar concept.

The nose cone prototype (see Figure 54) used in the test was milled out of Expanded Polypropylene (EPP) foam and was attached via glue for experimental purposes. It had a ground clearance of 400 mm which was representative of a standard HGV (Feist and Faßbender, 2008).

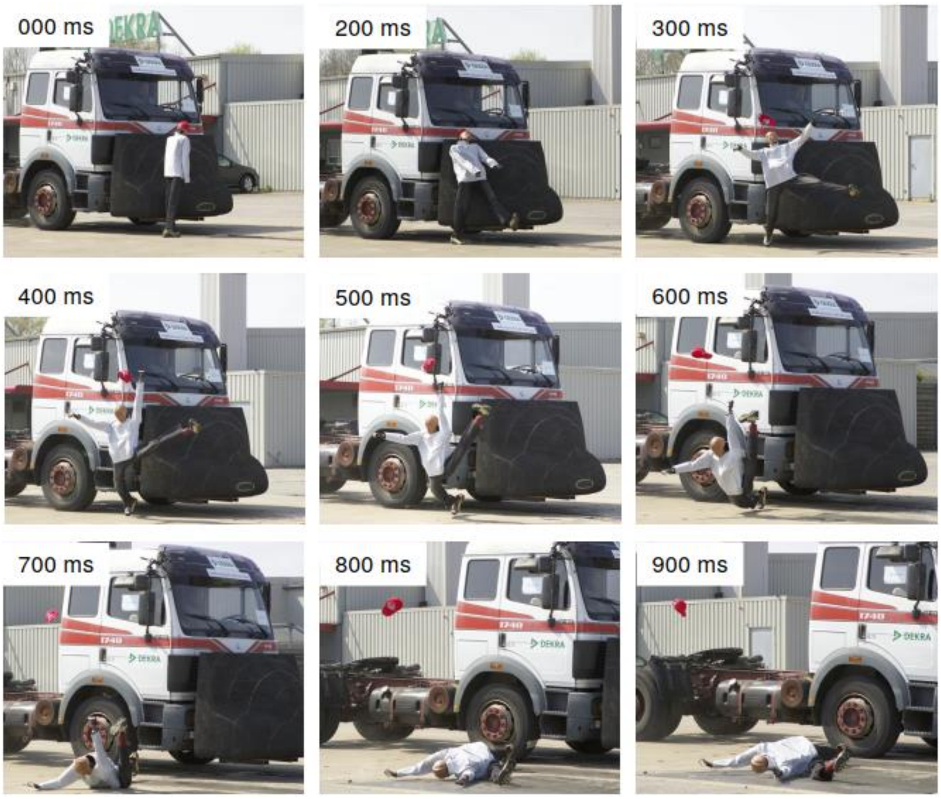


Figure 54: HGV with nose cone design fitted (Feist and Faßbender, 2008)

The results showed the nose cone was most effective at deflecting pedestrians at impact speeds below 30 km/h. At this speed approximately 80% of VRUs end up underneath the HGV, by deflecting them away, with the nose cone, this can be avoided. Further numerical simulations also indicated the VRU would encounter a less severe secondary impact when they hit the ground if struck by a HGV with a nose cone.

Feist and Faßbender (2008) concluded an add-on nose cone was not as effective as a fully integrated design. A HGV which had a cone design from its inception could have more space for improved Front Underrun Protection and a larger cab interior volume for the driver with better direct vison. This study is, at the time of writing, the only non-simulation study of a nose cone conducted that uses a moving HGV and test dummy.

The Safety Bar concept (see Figure 55) was a 20-70 kg add-on feature to the HGV (Feist and Faßbender, 2008). The bar would add between 130-200 mm on to the overall length of the vehicle however the potential increase offers up to 180 mm of crush depth for the impacting VRUs head and upper body. This is split between 80 mm of EPP foam and up to 100 mm of space between the frame and front of the cabin. This design would be most beneficial at impact speeds of around 20-30 km/h, as the severity of the primary impacts above this range need to be reduced for the VRU to survive.

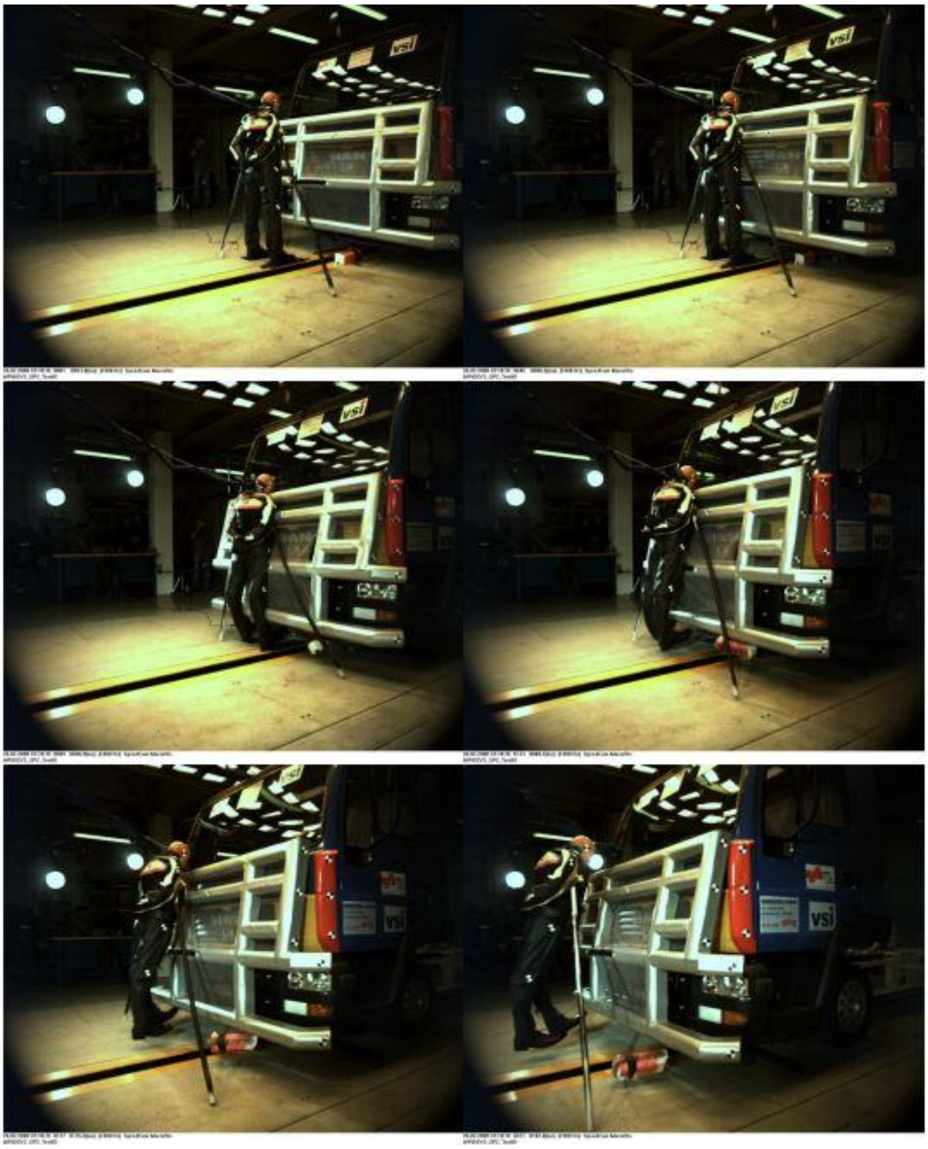


Figure 55: HGV fitted with Safety Bar striking a standing Hybrid 3 dummy (frames at -6, 40, 88, 136, 182, 230 ms) (Feist and Faßbender, 2008)

The results from the testing seen in Table 54 showed the device could reduce the HIC15 by up to 91% from 696 to 66; the peak head accelerations by 64-68%, the cumulative 3 ms acceleration value for both the chest and Pelvis by up to 51%, the sternum deflection by up to 42% and the femur peak accelerations by up to 85% (Feist and Faßbender, 2008).

Table 54: Hybrid 3 dummy injury results with and without a Safety Bar (Feist and Faßbender, 2008)

Impact location/ Safety bar fitted	HIC15 [ ]	NIJ [ ]	Stern. Deflect. [mm]	VC [m/s]	Chest cum3ms [G]	Pelvic Max. Acc. [G]	Pelvis cum3ms [G]	Femur Max. Acc. [G]	Femur cum3ms [G]
y=350 mm /No	696	0,80	63	0,50	68	81	76	168	98
y=-350mm /Yes	66	0,50	51	0,40	33	40	36	76	65
Change	*-91 %*	*-38 %*	*-19 %*	*-20 %*	*-51 %*	*-50 %*	*-53 %*	*-55 %*	*-34 %*
y=780 mm /No	438	0,90	74	1,60	49	96	67	300	120
y=780 mm /Yes	211	0,30	43	0,30	38	34	33	45	43
Change	*-52 %*	*-67 %*	*-42 %*	*-81 %*	*-22 %*	*-65 %*	*-51 %*	*-85 %*	*-64 %*

The 10-12 m VRU throwing distance (the distance between pre and post VRU position) was similar to real world scores which showed the addition of the bar did not have a negative influence on post primary impact injuries (Feist and Faßbender, 2008).

By using the Safety Bar Concept, Feist and Faßbender (2008) demonstrated it was possible to reduce the risk of injuries to head and lower extremities at impact speeds of up to 40 km/h (after which the EPP bottomed out) for between €400-600.

Annex 3.6 Fuso Concept HGV (Case Study 3)

Annex 3.6.1 Key safety measures

The four key safety measures adopted by the Fuso Concept HGV are:

- Direct Vision [DIR]
- Cameras [CAM] (Indirect Vision)
- Detection Sensors [DET] (Indirect Vision)
- VRU Impact Protection [VIP] (Passive Safety)

Annex 3.6.2 Concept overview

The Fuso Concept Truck was launched at the 38th Tokyo Motor Show in 2004 (Figure 56), along with two other concept HGVs (Fuso, 2004). This HGV was created to demonstrate how future models can be safer, more efficient and better for the environment.

Figure 56: Full scale model of the Fuso Concept HGV (Fuso, 2004)

The concept aims to provide the driver with a greater field of vision as well as improved crashworthiness structures (Fuso, 2004). Direct vision performance has been improved, compared to a production HGV, through the use of large glazed areas supplemented by additional side windows and semi-transparent A-pillars. Indirect vision performance was also considered by replacing the conventional side and under mirrors with cameras and equipping the vehicle with pedestrian monitoring sensors to help locate VRUs in the remaining blind spots. The vehicle also has a large crushable front bumper to reduce the impact of a collision with both cars and VRUs.

Annex 3.7 Volvo 2020 Vision Concept Truck (Case Study 4)

Annex 3.7.1 Key safety measures

The three key safety measures adopted by the Volvo 2020 Vision Truck are:

- Direct Vision [DIR]
- Cameras [CAM] (Indirect Vision)
- VRU Impact Protection [VIP] (Passive Safety)

Annex 3.7.2 Concept overview

The 2020 Vision truck concept (Figure 57) was unveiled in 2010 and demonstrated what Volvo Trucks thought future long distance haulage was going to look like in 2020 (Volvo Trucks Global, 2010).

Figure 57: Volvo 2020 Vision Concept Truck model (Volvo Trucks Global, 2010)

The extended lower section of the cab includes 'integrated collision protection'. This cab extension is approximately 500 mm and this is intended to both reduce collision forces and improve the aerodynamic performance of the vehicle.

The aim of this concept vehicle was to improve visibility and create an environment that was "spacious, airy and free of disruption". The design has a large windscreen and side windows on both sides of the cab, providing good visibility both in and out of the vehicle. The design also has no wing mirror clusters, as they have been replaced with a camera monitoring system.

The traditional dashboard (see Figure 58) has been replaced with a thin touch pad film panel to free up cab space and make the environment less claustrophobic. Furthermore, when the vehicle is parked up in a layby or service for a rest, the driver has the option to activate a privacy screen which can darken the window.

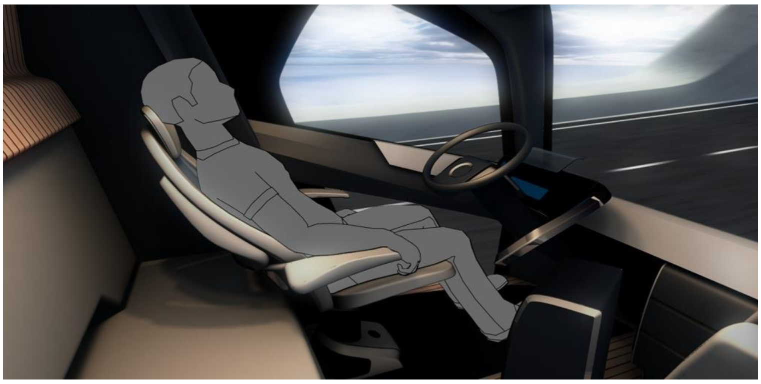


Figure 58: Volvo 2020 Vision Concept Truck Interior (Volvo Trucks Global, 2010)

Annex 3.8 Loughborough Design School (LDS) FKA Concept Truck (Case Study 5)

Annex 3.8.1 Key safety measures

The four key safety measures adopted by the FKA concept Truck are:

- Direct Vision [DIR]
- VRU Impact Protection [VIP] (Passive Safety)
- Front Underrun Protection System [FUP] (Passive Safety)

Annex 3.8.2 Concept overview

The FKA concept was developed from the findings of the APROSYS safer HGV front end work package (described in Case 2) and was designed to investigate how to optimise heavy vehicle safety and aerodynamics (Transport and Environment, 2012). In 2014 the FKA model was also adapted by the Loughborough Design School (LDS) for its measuring HGV direct vision project (Summerskill *et al.*, 2014).

To keep the FKA concept as realistic as possible, the model used the same seat, steering wheel adjustability, location of the pedal surfaces, mirrors and dashboard from a DAF XF105 baseline vehicle (Summerskill *et al.*, 2014).

Figure 59: Second literation of the modified FKA Concept Truck (Summerskill and Marshall, 2014)

The modified FKA model had three main iterations (Figure 59). Iteration 1 removed the passenger side of the dashboard structure to allow for further windows to be installed. This had the added effect of lowering the bottom edge of the windscreen and increasing the driver's field of view. The study questioned how removing a large section of dashboard would affect passenger airbag positioning; however these were found to be an optional extra. There were also further concerns over how removing the component would affect the overall cab strength but this was out of the scope of the project. LDS also looked into the benefits of removing the passenger seat or adopting folding passenger seat as these decrease the effectiveness of side windows however no existing data was found to support this idea. Single seat cabs are an occurring trend in concept trucks (particularly day cabs) as passengers are rarely carried. In the US, Freightliner has taken this idea a step forward with its 2012 Revolution Innovation concept truck and turned the passenger side of its cab into an office space (Freightliner, 2014). Despite these changes offside (driver side) front corner visibility required improvement.

Iteration 2 (Figure 60) added further additional cab windows and through analysing variations in cab height of various Scania models, lowered the cab height (and driver eye height), by 230mm. This was the most effective out of the variations for direct vision however it involved reducing the vehicle's ground clearance which would have affected the vehicle's off road capability.

Figure 60: Driver view from the second literation cab (Summerskill and Marshall, 2014)

The third iteration added a more severe taper to the cab and introduced a central driving position; this did not prove to be as effective as the instrument panel in the narrower cabin blocked the view of VRUs directly in front of the vehicle.

The FKA rounded nose cone utilises extruded aluminium alloy bumpers and crash boxes to help absorb the impact forces (Welfers *et al.*, 2011). In a series of computer simulations conducted by Welfers *et al.* (2011), the collision performance of the FKA concept was compared to a reference HGV modelled on a selection of equivalent vehicles from leading HGV manufacturers. Among the tests, the FKA concept was simulated in a head on collision (with and without a 30% offset) involving a car, a front of HGV to rear of car impact and a variety of VRU strikes.

The FKA concept demonstrated an improved and prolonged period of energy absorption during head on collisions compared to the reference HGV (see Figure 61) (Welfers *et al.*, 2011). Welfers *et al.* (2011)found the energy absorbed by the simulated car during a collision could be reduced from 130 kJ to 112 kJ and over a period of 13 ms instead of 10 ms.

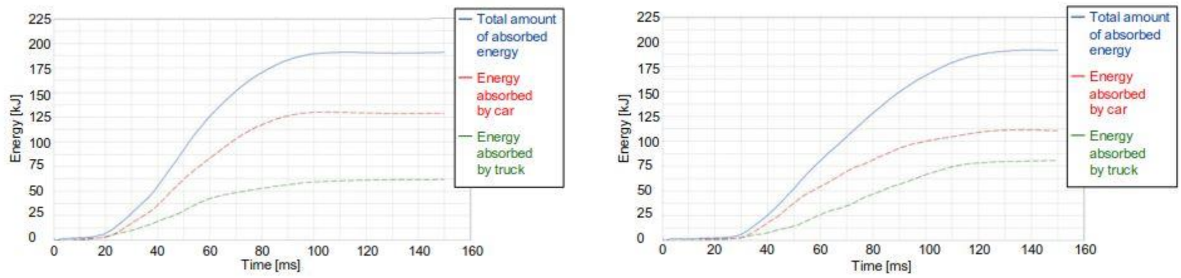


Figure 61: Energy absorption vs time for the reference HGV (left) and FKA concept (right) (Welfers *et al.*, 2011)

As a result of this the maximum intrusion in to the car's firewall and acceleration at the car's rear seats, with a 30% offset, was reduced from 186.1 mm (reference HGV) to 174.4 mm and 85 g to 70 g respectively (Welfers *et al.*, 2011). The overall intrusion caused by the FKA concept during the full width collision was less than the reference HGV apart from a small area in the upper right hand corner which was intruded by 187.3 mm compared to 175.9 mm (reference HGV). The maximum acceleration was reduced from 250 g down to 112.5 g with no offset.

Welfers *et al.* (2011) mentions a reduced intrusion in to the steering wheel area. This is important as it decreases the likelihood of the car occupant making contact with a component that could injure them however no values were given.

The enhanced front end design also proved beneficial during the front of HGV to rear of car type collisions. The intrusion in to the car's rear floor plan and peak acceleration was reduced from -80.2 mm down to -34.8 mm and 170 g to 59 g respectively.

In the VRU impact simulations, a six year old child, 5% female, 50% male and 95% male pedestrians were struck at the centre point and the edge of both nose designs. A 50% male cyclist was also simulated. Out of the nine simulations the reference HGV prevented overrun in three of the tests (six year old child, 5% female and 50% male struck at the edge of the nose), whereas the FKA concept prevented overrun in all nine tests using the FKA concept. Welfers *et al.* (2011)predicted that the 80 cm longer HGV nose could reduce up to 50% of HGV related fatalities, which is equivalent to 3200 to 3800 lives per year (in 2008) including 300 VRUs.

As well as collision partners, the simulations also assessed the level of damage inflicted to the HGV during the collisions. Four evaluation points along the chassis side members were chosen (see Figure 62). It was found the forces applied to the side members during the 30% offset, full width and rear end collision tests were reduced from 305 kN on average (reference HGV) to 240 kN, 427 kN to 235 kN and 90 kN to 74 kN respectively.

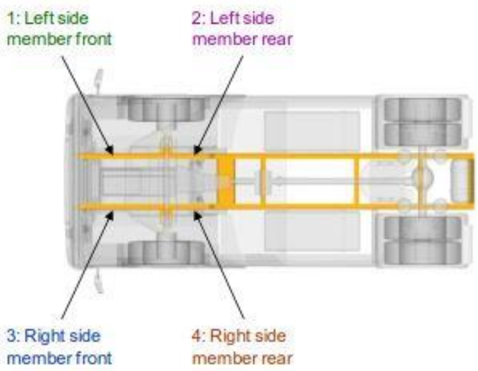


Figure 62: Collision force evaluation points (Welfers *et al.*, 2011)

Annex 3.9 MAN Concept S (Case Study 6)

Annex 3.9.1 Key safety measures

The three key safety measures adopted by the MAN concept S are:

- Cameras [CAM] (Indirect Vision)
- VRU Impact Protection [VIP] (Passive Safety)
- Front Underrun Protection System [FUP] (Passive Safety)

Annex 3.9.2 Concept overview

The MAN Concept S tractor unit and Krone Aeroliner semi-trailer combination (see Figure 63) was unveiled at the 2010 IAA Commercial Vehicle Show (Motor India, 2013). The design was primarily intended as an aerodynamic technology demonstrator, although offered a number of key opportunities for the integration of improvements in VRU and car occupant safety.

Figure 63: MAN Concept S with Krone Aeroliner semi-trailer scale model (Krone Trailer, 2012)

Although the extended cab was not optimised for frontal impact compatibility in this concept, it would contribute to improving crash safety through the increased size of the crumple zone. The curved frontal area would also deflect VRUs rather than under the vehicle.

The vehicle is equipped with a camera system instead of the typical large wing mirror clusters to further reduce drag.

Annex 3.10 Volvo V40 (Case Study 7)

Annex 3.10.1 Key safety measures

The two key safety measures adopted by the Volvo V40 are:

- Vulnerable Road User Airbag [VAB] (Passive Safety)
- Autonomous Emergency Braking with Pedestrian and Cyclist Detection [AEB-PCD] (Primary Active Safety)

Annex 3.10.2 Concept overview

The second generation Volvo V40 was launched in the 2012. It features many types of active and passive safety systems such as VRU Detection and Road Sign Recognition. This vehicle has been chosen as a case study as it was the first production car to have pedestrian airbags fitted to it (see Figure 64). Pedestrian airbags have since been fitted to the 2015 Land Rover Discovery Sport 2016 and Subaru Impreza.

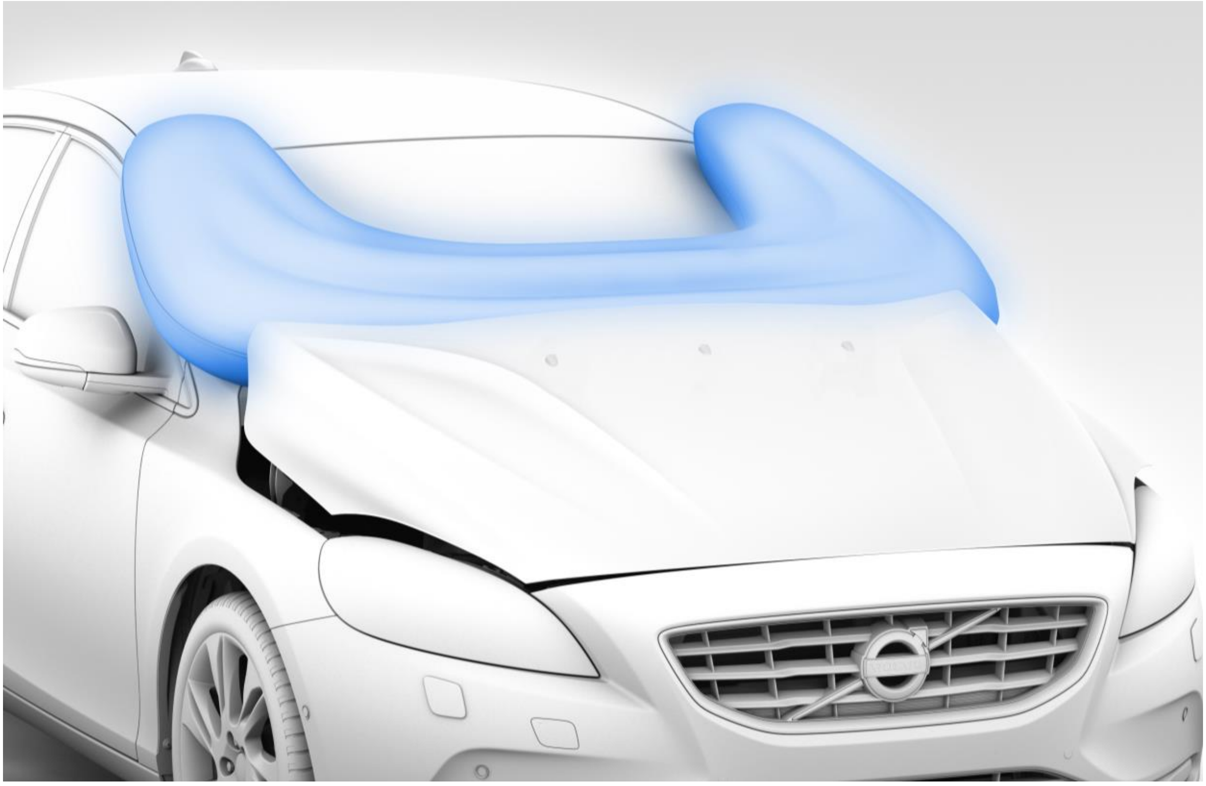


Figure 64: Volvo V40 VRU airbag deployed (Volvo Car Group, 2012)

The Volvo system works by the sensors located in the front bumper detecting a collision with an object similar to a human leg when the vehicle is travelling between approximately 20-50 km/h (Volvo Car Group, 2017). The windscreen end of the bonnet is released and raised 100 mm by the deploying airbag. Once fully inflated the airbag covers the bottom third of the windscreen and the lower half of the vehicles A pillars. Volvo claims their airbag could reduce pedestrian fatalities by 5% and serious injuries by up to 14% (Nightingale, 2012).

The Subaru airbag covers the same area as the Volvo, however deploys through a gap between the wipers and the bonnet; this does not require the bonnet to be raised and only requires one inflator instead of three which reduces the overall cost of the system. (Nikkei Technology, 2016). The Discovery Sport also deploys like this, in 60ms, and works between 25-30 km/h (Land Rover, 2016). It has been designed to ensure a safe minimum level of driver vision post inflation.

Annex 3.11 Low Entry Cab HGVs (Case Study 8)

Annex 3.11.1 Key safety measures

The seven common key safety measures adopted by Low Entry Cab configured HGVs are:

- Direct Vision [DIR]
- Cameras [CAM] (Indirect Vision)
- Detection Sensors [DET] (Indirect Vision)
- VRU Impact Protection [VIP] (Passive Safety)
- Autonomous Emergency Braking [AEB] (Primary Active Safety)
- Lane Departure Warning System [LDWS] (Primary Active Safety)

Annex 3.11.2 Concept overview

Low Entry Cabs (LEC) have been on the roads for many decades. It is only in the last few years, however, that the full potential of the LEC design has been realised. Today, manufacturers of this type have developed their models, once used primarily for refuse collection, to fit a multitude of urban roles such as tippers, box bodies and even tractor units (Pink, 2017). The uptake of LEC's in the UK is being encouraged by organisations such as Construction Logistics and Community Safety (CLOCS) and the future Direct Vision Standard (CLOCS, 2015;Robinson *et al.*, 2016).

Dennis Eagle manufactures 75% of low entry chassis supplied to UK local authorities and private sector contractors (The Pan-European Transport and Logistics Magazine, 2015). The Dennis Eagle Elite 1 was the first LEC refuse vehicle available in the UK, today the Elite 6 (see Figure 65) is now available in many forms, the latest being a 8x4/2 tridem (Tinham, 2016). This HGV has a 100 mm lower running height compared to the industry standard N3G.

Figure 65: Dennis Eagle Elite 6 (Dennis-Eagle, 2017)

The Elite is equipped with a range of primary active and indirect vision sensor technologies to increase driver situational awareness. Four cameras and a RADAR unit monitor the trajectory and speed of the vehicle under certain conditions (The Pan-European Transport and Logistics Magazine, 2015). Optical sensors that distinguish between black and white work with cameras capable of recognising road signs to give drivers audible warnings when the vehicle starts to stray across a lane into a potential cyclist. The Elite models were fitted with AEBS and LDWS before the mandatory fitment date.

The reduced cab heights and large glazed area provide a panoramic view which reduces the chances of the driver losing sight of cyclists or pedestrians in close proximity to the vehicle (Tinham, 2016). This has been achieved through having thin, singular, A and B-pillars (the Mercedes-Benz Econic has two per front corner). Another benefit of reducing the cab height is that the mirrors require less distortion to show nearby traffic which makes the images easier to interpret.

To enable off-road manoeuvring, the nose can be raised by 65-70mm at speeds up to 15 km/h to reduce the risk of damage because of low approach angles.

The Mercedes-Benz Econic (Figure 66) was originally launched in 1999 (London Cycling Campaign, 2013). Its Low Entry Cab allows the driver to sit approximately half a metre lower to the ground compared to an equivalent normal distribution cab which gives the driver a much better view and allows the them to make better eye contact with nearby VRUs. The driver has an increased field of vision through the use of six mirrors, a lower mounted dash board, A-pillars partially made of glass and a camera monitoring system. It is also fitted with an audible alarm to alert the driver when a cyclist is riding alongside the vehicle.

The Mercedes Econic costs approximately 15% more than a conventional cab and chassis (£65-100,000 depending on configuration) (London Cycling Campaign, 2013). The LEC platform is suitable for minor construction sites, but is limited in its off-road capability by its low ground clearance and large front overhang.

Figure 66: Mercedes-Benz Econic High Visibility Safety Truck demonstrator (Mercedes-Benz, 2017)

The Volvo FE LEC (see Figure 67) had its European debut in 2014 and uses a modified FE cab (Tinham, 2014). It has a 200 mm lower driving position than its donor vehicle and an 530 mm entry height, which can be reduce by a further 90 mm when using the kneeling function of the vehicle.

When driving, the driver can be alerted to VRUs using a close proximity warning system that uses four cameras fitted around the cab. Extra side windows behind the B-pillars and below the main side windows can be installed as an option. The driver seat is mounted forward of the crew seats to maximise the drivers field of view. As the cab has not been lowered to the same extent as dedicated LEC's, there is no need for an engine tunnel so the floor is flat throughout the cab.

Figure 67: Volvo FE LEC (Pink, 2016a)

The Scania Urban Tipper (see Figure 68) was launched at the 2016 Construction Logistics and Cycle Safety (CLOCS) exhibition (Scania, 2016). It is an 8x2*6 (3 steering axles and a single powered axle) configuration and uses a near standard Scania P cab on a N3 (HGV exceeding 12 tonnes) chassis to aid manoeuvrability and awareness in urban environments and public highways where 90–95% of the vehicle's driving time is expected to take place.

The Urban Tipper solves the N3g cab height issue by using full variable height air suspension. This allows chassis height to be lowered when the vehicle is driving in an urban environment which makes spotting VRUs easier for the driver and then raised when the vehicle returns to construction site. Some off-road capability is lost because of the single drive axle.

The vehicle is also fitted with additional side windows located in nearside (passenger) door and a camera monitoring system to supplement the direct vision. Along with a range of other active safety measures such as Electronic Stability Control, Lane Departure Warning System and Automated Emergency Braking System to assist driving the large vehicle.

Figure 68: Scania Urban Tipper Concept (Scania, 2016)

Annex 3.12 Iveco Z Truck (Case Study 9)

Annex 3.12.1 Key safety measures

The three key safety measures adopted by Iveco Z Truck are:

- Direct Vision [DIR]
- Cameras [CAM] (Indirect Vision)
- Detection Sensors [DET] (Indirect Vision)

Annex 3.12.2 Concept overview

The Iveco Z Truck (Figure 69) was launched at the 2016 IAA Commercial Vehicle Show. The concept was built around the idea of zero emissions, accidents, stress and waste of time (Iveco, 2016) and develops upon many of the ideas from the Iveco Vision Van (see Annex 3.14.2).

Figure 69: Iveco Z Truck full scale model (Iveco, 2016)

The concept has a large glazed area with the A-pillars to minimise obscuring the driver's field of view. It is important to note that, as a concept vehicle, structural strength has been set aside to demonstrate what can be done with driver visibility if this was not an issue (Iveco, 2016).

The vehicle has no mirrors as they have been replaced with cameras. The image is displayed on screens fitted to the inside of the A pillars as this is where the driver is used to looking, making the head movement and interpretation of where the image is relative to the vehicle feel more natural, and cannot further obstruct the drivers view. Both are common issues encountered by drivers when additional aftermarket screens are fitted (Cook *et al.*, 2011a). In addition to the A pillar mounted screens, there is a full cab width rear view screen mounted above the windscreen (Iveco, 2016).

Z Truck has a central seating position; the steering wheel system, pedals and control console are in a self-contained unit which removes the need for a large dashboard and opens up the cab for improved direct vision similar to the FKA concept.

Figure 70: Iveco Z Truck Interior (Iveco, 2016)

Only vital information is displayed to driver to prevent sensory overload. Key information is also displayed on a Heads-Up Display (HUD) to reduce the number of times the driver must look down at the IP (Iveco, 2016).

Annex 3.13 Camera and Detection Systems (Case Study 10)

Annex 3.13.1 Key safety measures

The three key safety measures adopted by detection systems are:

- Cameras [CAM] (Indirect Vision)
- Detection Sensors [DET] (Indirect Vision)
- Autonomous Emergency Braking [AEB] (Primary Active Safety)

Annex 3.13.2 Detection system overview

The aim of a detection system is to aid the driver in locating VRUs in close proximity to the vehicle. Vehicle manufacturers and aftermarket companies offer a large range of products with mixed capabilities and cost.

The Trailer Vision Omni-Vue 360° 'Look Down' wireless camera system is an aftermarket option which uses four 185° cameras to create a 360° blended bird's eye view around the vehicle it is installed to (Trailer vision, 2017). This has the potential to eliminate all blind spots if used correctly. The driver has the option to select a view from one of the individual cameras to display in a separate screen or allow the system to automatically switch to the appropriate camera during key manoeuvres such a turning right, to supplement the bird's eye view. This product can cost between £1500 and £2034 depending on the chosen specification. The Brigade Backeye 360 Camera Monitoring System product range offers similar capabilities (Brigade, 2017).

Brigades Ultrasonic Obstacle Detection, aftermarket, product range provides blind spot coverage to key areas surrounding a HGV in the form of Frontscan, Sidescan (offside and nearside), Cornerscan, Stepscan and Backscan (Brigade, 2017). Using this system, a driver can be alerted of an obstacle in less than 200 ms, by an audible warning. To prevent distraction, the devices have a choice of detection ranges, selectable via a dip switch, and an Environment Learning Mode to prevent false alarms due to vehicle components, such as tow hooks, situated within the first 1 m of the detection zone. Frontscan uses four sensors and has a detection range of 2.0 m or 1.0 m; the detection range of the outer sensors can be further reduced to 0.6 m if required. Sidescan uses four sensors and has a detection range of 1.0 m or 1.5 m and costs between £183 to £453 depending on whether the HGV is rigid or articulated (FORS, 2016). An additional Sidescan sensor for both sides of the cab can be installed if requested (Brigade, 2017). Cornerscan uses three sensors and has a detection range of 0.6 m or 1.0 m, Stepscan uses two sensors and has a 0.6 or 1.0 m finally Backscan uses four sensors which have a detection range of 2.5 m or 0.6 m (a 1.5 m is also available if required).

Active Brake Assist 4 was introduced in December 2016 and is the current iteration of the Mercedes-Benz Active Brake Assist series (Daimler, n.d.). The system is split in to two main sections, a long and short range detection system. The long range RADAR scans the view directly in front of the vehicle (opening angle of 18°) and can identify vehicles, motorcycles and pedestrians at a distance of 250 m, 160 m and 80 m respectively. The short range RADAR has a range of just 70 m but has an opening angle of 120°, this allows it to locate vehicles and VRUs to the sides of the vehicle. The automatic warning and braking functions between 0 km/h to 90 km/h however is most effective at speeds up to 50 km/h. Unlike many systems, Active Brake Assist 4 will automatically start introducing the brakes during the warning stage to prevent sudden deceleration. If the system notices the driver is not braking hard enough it will take over.

The Mercedes-Benz Sideguard Assist is intended to aid the driver when turning right or changing lanes (Daimler, n.d.). The system uses two short range RADAR sensors, installed to the front of the HGVs rear axle on the nearside, to create a side zone which extends 3.75 m from the side of the vehicle, 2 m from the front and 1 m from the end. A driver is alerted to a VRU in the detection zone by a triangular LED lighting up in line with the driver's eye level on the nearside A-Pillar. If the driver does not react an additional visual and audible warning is triggered. The LED will flash for two seconds then remain permanently on and a warning buzzer will sound from the relevant side of the radio system. The tracking warning functions between 0 to 36 km/h. The other functions remain operational up to 90 km/h. The German Insurance Association (GDV) believes the use of systems similar to this could prevent half of all HGVs versus VRU accidents, reduce the number of fatalities by approximately a third and the number of severely injured by 40% in Germany.

WABCO OnCity Urban Turn Assist is a single sensor system designed especially for HGVs, buses and trailers and is the first commercial vehicle collision avoidance system to use LIght Detection And Ranging (LIDAR is similar to RADAR but uses light instead of radio waves) (WABCO, 2016). The system works by continuously scanning a 180° field of view up to a distance of 25 m. It is able to identify when the vehicle is about to turn to the nearside and provides the driver with an audible and visual warning if any VRUs are detected with the blind spot. If the driver fails to take action then the system is able to apply the brakes automatically.

This brief review of VRU detection systems found aftermarket solutions tend to have a smaller detection range (0 m to 3 m) compared to integrated systems (0 m to 250 m). It was not possible to find the cost for the majority of the systems discussed in this section. However it is likely the integrated solutions would be more expensive due to the complexity of linking them to other components such as the brakes.

Other systems which were investigated included the Volvo bus Pedestrian and Cyclist Detection System, Mobile eye Safety shield, Continental ASL360 and cycle alert systems.

Annex 3.14 Other Noteworthy Cases

This section highlights a select number of non-European HGVs and non-HGV vehicles relevant to specific safety measures.

Annex 3.14.1 Direct visibility safety measures

Walmart Advanced Vehicle Experience (WAVE) (see Figure 71) was launched in 2014 and features cutting edge aerodynamics, use of materials (first carbon fibre semi-trailer) and a hybrid gas turbine powertrain (Walmart, 2014).

Figure 71: Walmart Advanced Vehicle Experience (Walmart, 2014)

The cab (see Figure 72) tapers in at the front end providing a central driving position. This combined with a large glazed area, side windows on both sides and camera system gives the driver an excellent field of vision. The central control console is designed to prevent blocking the view in front of the HGV. The gas turbine allows a more compact design allowing a short nose compared to diesel powered trucks. This is a good visual example of what could be achieved in Europe (Walmart, 2014).

Figure 72: WAVE interior (Walmart, 2014)

Annex 3.14.2 Indirect visibility safety measure

The 2014 Iveco Vision uses cameras instead of wing mirrors, the view is displayed on a full cab width screen displayed above windscreen. The design also features semi-transparent A pillars for improved direct vision (Iveco, 2017).

Figure 73: Iveco Vision Concept van interior (Iveco, 2017)

The Mercedes-Benz Urban eTruck (see Figure 74) was unveiled in 2016. The truck uses cameras instead of wing mirrors and also features a unique two screen data display method rather than a standard set of instruments. The main central screen displays key manoeuvres such as bends to pre-warn the driver, the second is a tablet that provides additional route data (Daimler, 2016).

Figure 74: Mercedes-Benz Urban eTruck camera system (Daimler, 2016)

Annex 3.14.3 Secondary passive safety measures

The Scania Truck of the 2010s (see Figure 75) was unveiled in 1999 and was the first concept HGV to include a short bonnet. This was achieved through having a 'retracted cab position' rather than an enhanced front end. The bonnet was designed to improve HGV to car collisions and provided a minor improvement on direct vision.

Figure 75: Full scale prototype of Scania 2010 Concept truck (Scania, 2017)

The XFC (Xtreme Future Concept) (Figure 76) was launched at the 2002 IAA Commercial Vehicle Show and is an example of how DAF incorporated an extended nose in to a HGV for improved crashworthiness and aerodynamics (Welfers *et al.*, 2011).

Figure 76: DAF XFC render (Welfers *et al.*, 2011)

The 2016 Nikola One Concept (See Figure 77) is the first hydrogen powered Class 8 (heaviest conventional weight category in the United States) truck. Similar to the WAVE, its powertrain allows a much shorter nose and is a good visual example of what European truck front ends could look like (Nikola Motors, 2017a).

Figure 77: Nikola One concept truck (Nikola Motors, 2017b)

Several ideas regarding passive safety, which were not taken forward in the APROSYS SP2 project (Bovenkerk and Fassbender, 2006), include:

- A deployable active bumper system that works by coming in contact with the feet or lower leg of the VRU before their upper body causing the VRU to go in to a spin and reduce the impact speed against the cab.
- A retractable bonnet controlled by a series of pneumatic actuators. When the vehicle travels less than 40 km/h this bonnet extends 80-100 mm to create a softer impact zone.
- An adaptive front grille works in a similar way to the retractable bonnet; however the actuators push the hinged grille sections out. This is most effective on larger HGVs due to their larger grilles.
- A VRU bumper module scooper is lowered when sensors fitted to the front of the HGV detect it has struck a VRU. The scooper could take the form of a flexible matt secured to the bottom of the chassis which prevents the VRU from coming in contact with the front wheels

Annex 3.14.4 Case study summary

A summary of the relevant information found from reviewing the selected vehicles can be found in Table 55.

Table 55: Summary of findings from the case studies

Safety Measure	Effectiveness	Cost
Direct Vision	N/A	The Econic Low Entry Cab costs approximately 15% more than a conventional cab and chassis (London Cycling Campaign, 2013).
Indirect Vision (Cameras and Detection Systems)	Mercedes-Benz Sideguard Assist could prevent half of all HGVs versus VRU accidents and reduce the number of fatalities by approximately a third and the number of severely injured by 40% in Germany (Daimler, n.d.).	Trailer Vision Omni-Vue 360° costs between £1500 and £2034 depending on the chosen specification (Trailer vision, 2017). Brigade Sidescan costs between £183 to £453 depending on whether the HGV is rigid or articulated (FORS, 2016).
Frontal Impact Compatibility	The Safety Bar demonstrated it was possible to reduce the risk of injuries to head and lower extremities by up to 90% at impact speeds of up to 40 km/h (Feist and Faßbender, 2008).	A Safety Bar would cost between €400-600 (Feist and Faßbender, 2008).
Front Underrun Protection	A 80cm longer HGV nose could reduce up to 50% of HGV related fatalities. Or 3200-3800 lives per year (in 2008) including 300 VRUs (Welfers *et al.*, 2011). The Scania CZC EA-FUP could increase the survivable collision speed from 56 to 90 km/h (Commercial Motor Archive, 2009a). The Scania CZC EA-FUP could have prevented up to 900 HGV to car frontal collision related fatalities per year at the time of launch (Commercial Motor Archive, 2009a)	N/A
VRU Airbag	Volvo claims their pedestrian airbag can reduce fatalities by 5% and serious injuries by up to 14% (Volvo Car Group, 2017).	N/A

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