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The Transport for London Bus Safety Standard: Direct Vision, Indirect Vision and Detection of Vulnerable Road Users

Evaluation of Safety Measures

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Report details

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1.1	30/07/2022	Corrections to Table 1 Added reference to TfL for latest specification in the executive summary and recommendations	AE	PSM & DH

Executive summary

Bus Safety Standard (BSS)

The Bus Safety Standard (BSS) is focussed on vehicle design and safety system performance and their contribution to the Mayor of London's Transport Strategy. This sets a target to achieve zero road collision deaths involving buses in London by 2030.

To develop the standard a large body of research and technical input was needed, so Transport for London (TfL) commissioned TRL (the Transport Research Laboratory) to deliver the research and consult with the bus industry. The delivery team has included a mix of engineers and human factors experts, to provide the balance of research required.

All TfL buses conform to regulatory requirements. TfL already uses a more demanding specification when contracting services and this requires higher standards in areas including environmental and noise emissions, accessibility, construction, operational requirements, and more. Many safety aspects are covered in the specification such as fire suppression systems, door and fittings safety, handrails, daytime running lights, and others. However, the new BSS goes further with a range of additional requirements, developed by TRL and their partners and peer-reviewed by independent safety experts. Accompanying the specification there are guidance notes to help inform the bus operators and manufacturers of what the specification is aiming to achieve and some practical tips on how to meet the requirements.

For each safety measure considered, a thorough review was completed covering the current regulations and standards, the specification of the current bus fleet and available solutions.

Full-scale trials and testing were also carried out with the following objectives. Firstly, the tests were used to evaluate the solutions in a realistic environment to ensure that a safety improvement was feasible. Secondly, the testing was used to inform the development of objective test and assessment protocols. These protocols will allow repeatable testing according to precise instructions so that the results are comparable. The assessment protocol provides instructions for how to interpret the test data for a bus or system, which can be a simple pass/fail check, or something more complex intended to encourage best practice levels of performance. These assessment protocols will allow TfL to judge how well each bus performs against the BSS and will allow a fair comparison in terms of safety if they have a choice between models for a given route.

It is important to ensure the money is spent wisely on the package of measures that will give the most cost-effective result. If zero fatalities can be achieved at a low cost it remains better than achieving it at a higher cost. TRL has developed a cost-benefit model describing the value of implementing the safety measures, both in terms of casualties saved and the technology and operational costs of achieving that. Input from the bus industry has formed the backbone of all the research and the cost benefit modelling. This modelling has helped inform the decisions of TfL's bus safety development team in terms of implementing the safety measures on new buses.

This research was completed in 2018. The detailed specification, assessment procedures and guidance notes have been incorporated into the Transport for London specification for buses, which is a continuously updated document to keep pace with the latest technological and research developments. This report is not the specification for a bus and should not be used as such. Bus operators, manufacturers, and their supply chain should consult with TfL for the specification.

Direct and indirect vision

This safety measure can be described as a Driver Assistance measure that helps the driver to avoid or mitigate the severity of an incident. Specifically, it concerns the driver's ability to respond to imminent collisions based on how well they can see out of and around the bus. Direct vision is concerned with what is in the driver's sightline, whereas indirect vision concerns blind spot visibility through use of mirrors or camera systems. Compared with HGVs, buses generally have better direct vision because they are relatively low to the ground with large windows. However, the regulatory requirements for indirect vision are much less demanding for buses than for HGVs and so blind spots remain. The BSS will incorporate requirements to minimise direct vision obstructions from pillars and improve indirect vision via the use of mirrors, or blind spot information systems and Camera Monitor Systems (CMS) in the future.

Bus Vision Standard

The assessment approach is based on the similar standard TfL are implementing for HGVs. However, it has been adapted to suit the different technical challenges presented by buses. It is based on defining a volume of space around the bus, where other road users may be positioned and at risk when the bus is manoeuvring. It measures how much of the volume can be seen by the driver. It considers the view from both direct and indirect vision and includes consideration of potential internal obstructions such as those that can be caused either by pillars or reflections on some assault screens. It uses sophisticated computer techniques to ensure a complex measurement process can be undertaken with minimal effort and be easily incorporated in the design process by bus manufacturers.

The assessment zones are divided into different areas and weighted in terms of the number of casualties associated with them. Separate research by the TfL freight team has shown direct vision to be preferable to mirrors so minimum standards have been set separately for the score that must be achieved by direct vision alone, and the overall score that must be achieved by both direct and indirect vision together.

The test and assessment protocol permits the substitution of mirrors by camera monitor systems (CMS), provided they comply with the relevant regulations. This approach removes the risk of a mirror hitting a pedestrian but is very new and the effect on driver workload and behaviour is not yet well documented. There may be opportunities for further benefits in minimising blind spots and helping drivers to see hazards around them, but there may be risks if drivers do not find them as natural to use. These will be considered a requirement in future, subject to evidence confirming the balance of risks and opportunities, and research to better define the specification.

Blind spot detection systems

Good direct and indirect vision alone will not eliminate all casualties in manoeuvring collisions; the driver must still be looking in the right direction at the right time. Systems that give the driver additional information about the hazards around the bus, or warn of an imminent collision, still have an important role to play. How this information is communicated to the driver is critical to their success and a draft standard accounting for different functionalities, the avoidance of false alarms, and the appropriateness of the human machine interface (HMI) has been developed.

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1 Introduction to the Bus Safety Standard (BSS)

1.1 The BSS

In 2018 the Mayor of London, Sadiq Khan, set out a ‘Vision Zero’ approach to road casualties in his transport strategy (Transport for London (TfL), 2018). It aims for no one to be killed in, or by, a London bus by 2030 and for deaths and serious injuries from road collisions to be eliminated from London’s streets by 2041. Transport for London (TfL) commissioned the Transport Research Laboratory (TRL) to deliver a programme of research to develop a BSS as one part of its activities to reduce bus casualties. The goal of the BSS is to reduce casualties on London’s buses in line with the Mayor of London’s Vision Zero approach to road safety. The BSS is the standard for vehicle design and system performance with a focus on safety. The whole programme of work includes evaluation of solutions, test protocol development and peer-reviewed amendments of the Bus Vehicle Specification, including guidance notes for each of the safety measures proposed by TfL. In parallel to the detailed cycle of work for each measure, the roadmap was under continuous development alongside a detailed cost-benefit analysis and on-going industry engagement. The BSS programme is illustrated below in Figure 1.

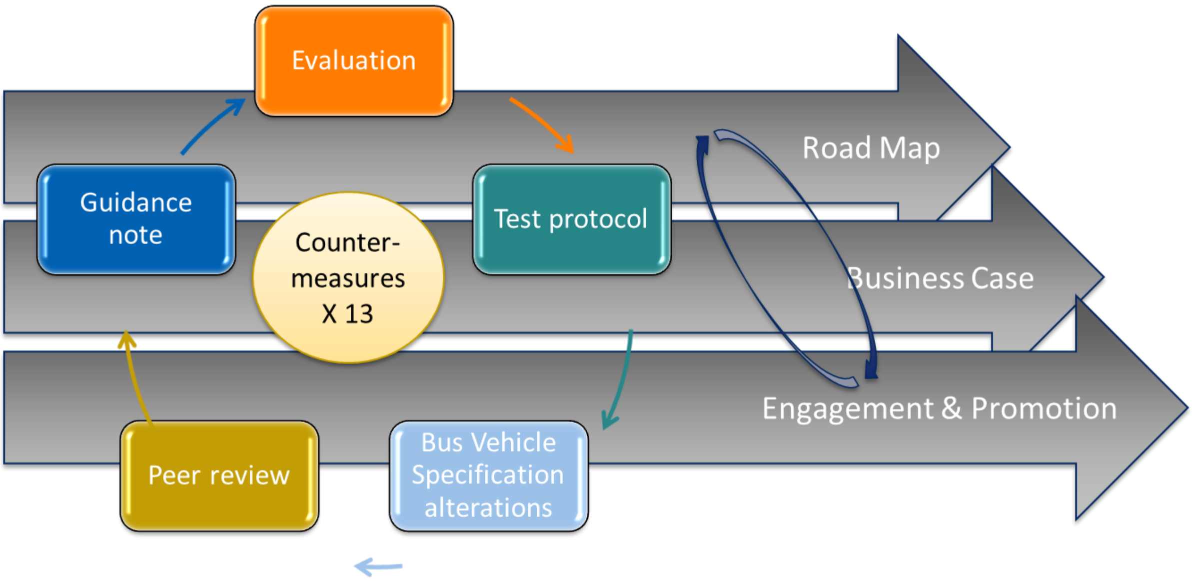


Figure 1: Summary of the BSS research programme

The exact methodology of the testing development depended upon each of the measures being developed. For AEB it included track testing and on-road driving, whereas for the occupant interior safety measures it involved computer simulation and seat tests. There was also a strong component of human factors in the tests e.g. human factors assessments by our team of experts. In addition, there were objective tests with volunteers to measure the effect of technologies on a representative sample of road users, including bus drivers and other groups as appropriate to the technology considered.

The test procedures developed were intended to produce a pass/fail and/or performance rating that can be used to inform how well any technology or vehicle performs according to the BSS requirements. The scenarios and/or injury mechanisms addressed were based on injury and collision data meaning it is an independent performance-based assessment.

A longer-term goal of the BSS is to become a more incentive-based scheme, rather than just a minimum requirement. The assessments should provide an independent indicator of the performance of the vehicle for each measure, and they will also be combined in an easily understood overall assessment.

It is important to ensure the money is spent wisely on the package of measures that will give the most cost-effective result. If zero fatalities can be achieved at a low cost, it remains better than achieving it at a higher cost. TRL has developed a cost-benefit model describing the value of implementing the safety measures, both in terms of casualties saved and the technology and operational costs of achieving that. Input from the bus industry has formed the backbone of all the research and the cost-benefit modelling. This modelling has helped inform the decisions of TfL's bus safety development team in terms of implementing the safety measures on new buses.

1.2 Bus safety measures

The measures selected for consideration in the BSS were wide ranging, as shown in Figure 2. Some will address the most frequent fatalities, which are the group of pedestrians and cyclists killed by buses, mostly whilst crossing the road in front of the bus. There are several measures that could address this problem, for example, Advanced Emergency Braking (AEB, which will apply the vehicle's brakes automatically if the driver is unresponsive to a collision threat with a pedestrian) or improved direct and indirection vision for the driver. These are both driver assis safety measures, which are designed to help the driver avoid or mitigate the severity of incidents. Intelligent Speed Assistance (ISA) is another example of driver assist, and TfL has already started rolling this out on their fleet. The last two driver assist measures are pedal application error (where the driver mistakenly presses the accelerator instead of the brake) and runaway bus prevention; both of which are very rare but carry a high risk of severe outcomes.

Visual and acoustic bus conspicuity are both partner assistance measures that are designed to help other road users, particularly pedestrians and cyclists, to avoid collisions. Partner protection is about better protection if a collision should occur. For this the work has started with Vulnerable Road User (VRU) front crashworthiness measures, including energy absorption, bus front end design, runover protection and wiper protection.

Passenger protection is focussed on protecting the passengers travelling on board the bus, both in heavy braking and collision incidents. This encompasses occupant friendly interiors inspections, improved seat and pole design, and slip protection for flooring. This group of measures that help to protect bus occupants are important because around 70% of injuries occur without the bus having a collision.

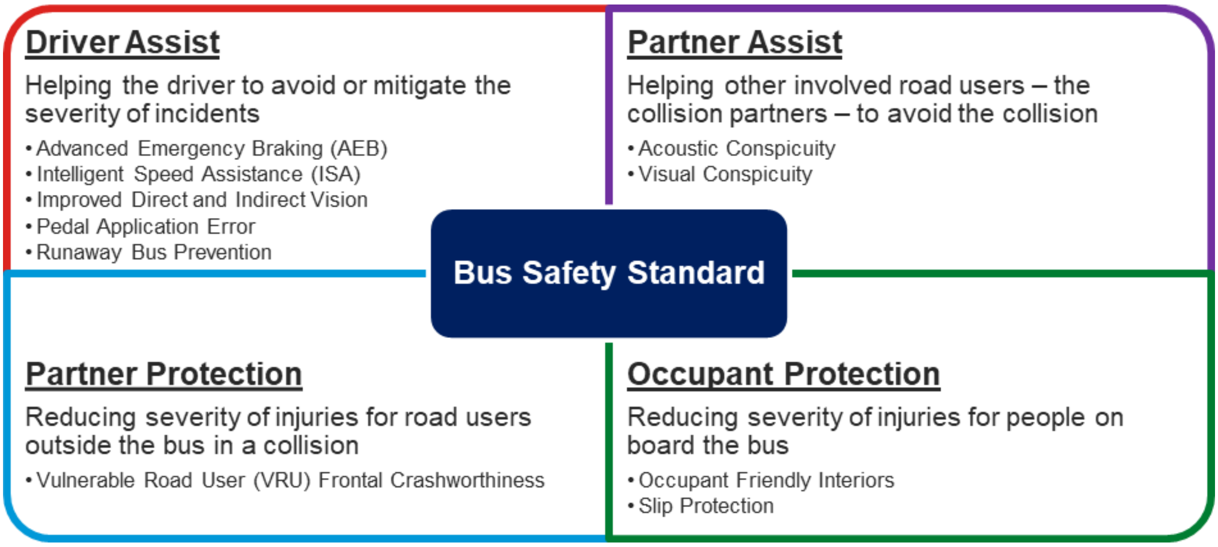


Figure 2: Bus safety measures

1.3 Direct and Indirect Vision (DIV)

The Direct and Indirect Vision (DIV) safety measure was used to investigate different approaches for specifying field of vision requirements that aim to prevent collisions from occurring due to drivers being unaware of VRUs in close proximity to the bus during low-speed manoeuvres. The DIV safety measure was split in to four functional categories;

- **Direct Vision (DIR):** The DIR safety measure focused on the field of view the driver has through the glazed areas of the bus by turning their eyes/head to observe VRUs in close proximity to the bus front end.
- **Indirect Vision (IND):** The IND safety measure, however, focused on the field of view the driver has via indirect vision devices, such as mirrors and camera monitor systems (CMS).
- **Internal Obscurations (IOB):** The IOB safety measure aimed to specify the requirements for internal obstructions, such as driver assault screens, to ensure the presence of internal components do not conflict with DIR/IND requirements during real-world operations.
- **VRU Detection (DET):** The DET safety measure will focus on sensor-based detection systems capable of detecting VRUs in close proximity to the nearside, offside and front-end of the bus.

For all four measures, the following sections define the relevant target populations, review the technological state-of-the-art in terms of solutions to help improve driver vision, research the effectiveness of each solution in preventing/mitigating VRU injuries, summarise both current and future legislative requirements and specify relevant testing and assessment protocols for the future Bus Safety Standard (BSS).

2 Defining the problem

2.1 Casualty priorities for TfL

Transport for London's aim in implementing the Bus Safety Standard is to assist in achieving 'vision zero' on the principle that no loss of life is acceptable or inevitable. Thus, the largest focus is on incidents resulting in death or serious injury. However, TfL recognise the disruption and cost that minor collisions can have for bus operators and the travelling public alike. Thus, safety features that can reduce the high frequencies of incidents of damage only and/or minor injury are also included within the scope of this project. The high-level matrix below in Table 1 categorises and prioritises groups of casualties involved in collisions with a single bus/coach[1] based on past data for London derived from the GB National Collision Database (STATS19).

Table 1 shows that over the past decade the highest priority casualty group in terms of death and serious injury from collisions involving buses in London has been pedestrians. Pedestrians killed or seriously injured in collisions where the bus was coded as going ahead (without negotiating a bend, overtaking, starting or stopping, etc.) and the pedestrian coded as crossing the road accounted for the largest proportion of these pedestrians.

2.2 Direct and indirect vision casualty problem

The purpose of this section is to perform a review of target populations associated with the Direct and Indirect Vision (DIV) safety measure. The target population is defined as the total number of fatalities or injured casualties which a particular safety measure is intended to address. A key factor in identifying the target population includes characterising the collision scenarios for which the safety measure is intended. This includes identifying causation factors, vehicle manoeuvres, opponent manoeuvres, impact configuration and collision severities in addition to understanding any differences between these characteristics based on vehicle or casualty types.

In the following subsections the collision landscape data relevant to the DIV safety measure and available from national (STATS19) collision databases is reviewed alongside supplementary evidence available from across the literature. The following subsections therefore review the current evidence base underpinning the estimation of target populations associated with each of the four functional safety categories. A summary of overall target population values, for each functional safety category is presented in section 2.6.

[1] Single vehicle collisions, which involve a single bus/coach striking either vulnerable road users (VRU: pedestrians, cyclists or powered two wheelers (PTWs)) or another single vehicle, are only included in this analysis to remove the potential for confounding data from multi-vehicle collisions where it would be challenging to determine whether a certain solution would be effective or not.

Table 1: Casualty prevention value attributed to different collision types; London STATS19 data from 2006-15 (%)

Casualty Type	Collision type	Fatal	Serious	Slight	KSI	Total
Bus Passenger	Injured in non-collision incidents - standing passenger	4.2%	17.1%	23.3%	11.9%	15.2%
	Injured in non-collision incidents - seated passenger	0.5%	6.4%	13.0%	4.0%	6.6%
	Injured in non-collision incidents - boarding/alighting/other	1.6%	7.6%	5.3%	5.2%	5.2%
	Injured in collision with a car	0.5%	4.6%	10.1%	2.9%	5.0%
	Injured in collision with another vehicle	0.0%	3.1%	5.0%	1.8%	2.8%
	Total	6.9%	38.7%	56.7%	25.9%	34.8%
Pedestrian	Injured in a collision while crossing the road with a bus travelling straight ahead	30.7%	20.0%	7.0%	24.3%	19.3%
	Injured in a collision, not while crossing the road, with a bus travelling straight ahead	10.6%	7.9%	4.6%	9.0%	7.7%
	Injured in a collision with a bus turning left or right	12.2%	3.1%	1.2%	6.8%	5.2%
	Injured in other collision with a bus	2.1%	1.4%	0.7%	1.7%	1.4%
	Total	55.6%	32.5%	13.6%	41.8%	33.6%
Car Occupant	Injured when front of bus hits front of car	6.3%	1.9%	0.9%	3.7%	2.9%
	Injured when front of bus hits rear of car	1.6%	0.8%	2.8%	1.1%	1.6%
	Injured when front of bus hits side of car	1.1%	1.1%	1.8%	1.1%	1.3%
	Injured in side impact collision with a bus	2.6%	1.9%	3.9%	2.2%	2.7%
	Injured in other collision with a bus	2.1%	1.0%	1.4%	1.5%	1.4%
	Total	13.8%	6.6%	10.8%	9.5%	9.9%
Cyclist	Injured in a collision with the front of a bus travelling straight ahead	2.1%	1.2%	0.9%	1.5%	1.4%
	Injured in a collision with another part of a bus travelling straight ahead	0.0%	2.6%	1.5%	1.6%	1.6%
	Injured in a collision with the nearside of a bus which is turning	1.6%	0.8%	0.4%	1.1%	0.9%
	Injured in other collision with a bus	0.5%	3.1%	2.1%	2.1%	2.1%
	Total	4.2%	7.8%	5.0%	6.4%	6.0%

Casualty Type	Collision type	Fatal	Serious	Slight	KSI	Total
Powered Two Wheeler (PTW)	Injured in a collision with a bus travelling straight ahead	2.6%	1.3%	0.7%	1.9%	1.5%
	Injured in a collision with a bus turning left or right	0.5%	1.0%	0.7%	0.8%	0.8%
	Injured in other collision with a bus	0.5%	1.0%	0.9%	0.8%	0.8%
	Total	3.7%	3.4%	2.3%	3.5%	3.2%
Bus Driver	Injured in collision with a car	0.0%	1.5%	2.5%	0.9%	1.4%
	Injured in non-collision incidents	0.0%	0.5%	0.5%	0.3%	0.4%
	Injured in collision with another vehicle	0.5%	1.2%	1.5%	1.0%	1.1%
	Total	0.5%	3.2%	4.5%	2.1%	2.8%
Other	**Total**	**15.3%**	**7.9%**	**7.1%**	**10.9%**	**9.8%**
Casualties Total		**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

2.3 Top-level collision landscape

For the Direct and Indirect Vision (DIV) safety measure, the TfL BSS requires the consideration of VRU impacts (pedestrians, cyclists and powered two-wheelers (PTWs)) against buses within the Greater London region. Analysis of the STATS19 database has shown that there were 20,404 collisions involving a single bus or coach in Greater London during the period 2006-2015, resulting in a total of 24,678 casualties. These casualties, broken down by injury severity level, are shown in Table 2 for all VRU casualties and for pedestrians, pedal cyclists and PTWs only.

Table 2: Number of casualties by injury severity due to collisions involving a bus or coach in London between 2006-2015 (data source: STATS19)

	All Casualties	Pedestrian Casualties	Cyclist Casualties	PTW Casualties	All VRU Casualties
Fatalities	189	108	8	7	123
Seriously Injured	2,477	816	176	84	1,076
Slightly Injured	22,012	2,997	1,093	510	4,600
Total Casualties	24,678	3,921	1,277	601	5,799

STATS19 data showed there was a total of 5,799 VRU casualties from collisions with a bus or coach, which means that VRU casualties make up 23% of all casualties due to collisions involving buses and coaches in London. Figure 3 shows the distribution by road user type for each injury severity. VRUs account for 21% of all slight casualties, 43% of all serious casualties and 65% of all fatalities. Pedestrians are a particularly vulnerable VRU, accounting for 14% of all slight casualties, 33% of all serious casualties and 57% of all fatalities This highlights that VRUs, and in particular pedestrians, are more vulnerable to being seriously or fatally injured as a result of a collision with a bus or coach supporting the need for the DIV safety measure.

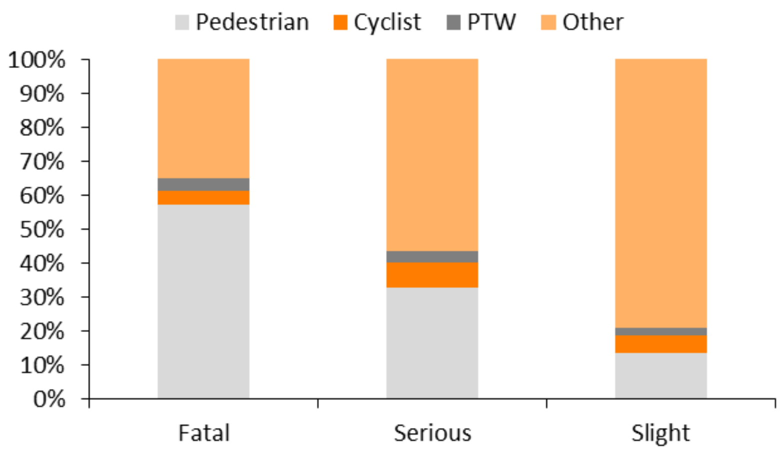


Figure 3: Distribution of casualties by road user type and for each injury severity in collisions involving a single bus or coach in London between 2006-2015 (data source: STATS19)

2.4 Relevant driver fields of vision

It is important for the DIV safety measure to quantify the target populations according to the relevant driver fields of vision that each safety measure solution is designed to improve. The challenge with this approach is that STATS19 does not code collisions by the fields of vision that VRUs move through when involved in collisions with a bus. Contributory factors can be used to determine when a VRU may have been in the blind spot of a bus or when a bus driver may have failed to look properly, however, these do not provide further information on which field of vision a particular collision was relevant to.

2.4.1 UN Regulation Number 46 (UN R46)

UN R46 (Indirect Vision Devices) may be used to define the relevant fields of vision for a bus (see Figure 4, with further information in Section 5.1.2). Although Figure 4 illustrates all field of vision zones defined by UN R46, it is important to note that only the Class II field of vision zone is currently mandated for M3 category vehicles (buses/coaches). These field of vision zones may then be linked to certain collision configurations that are defined by the manoeuvres and impact points of both the bus and the VRU. Finally, each safety measure solution can then be linked to a single, or combination of, relevant field of vision zones.

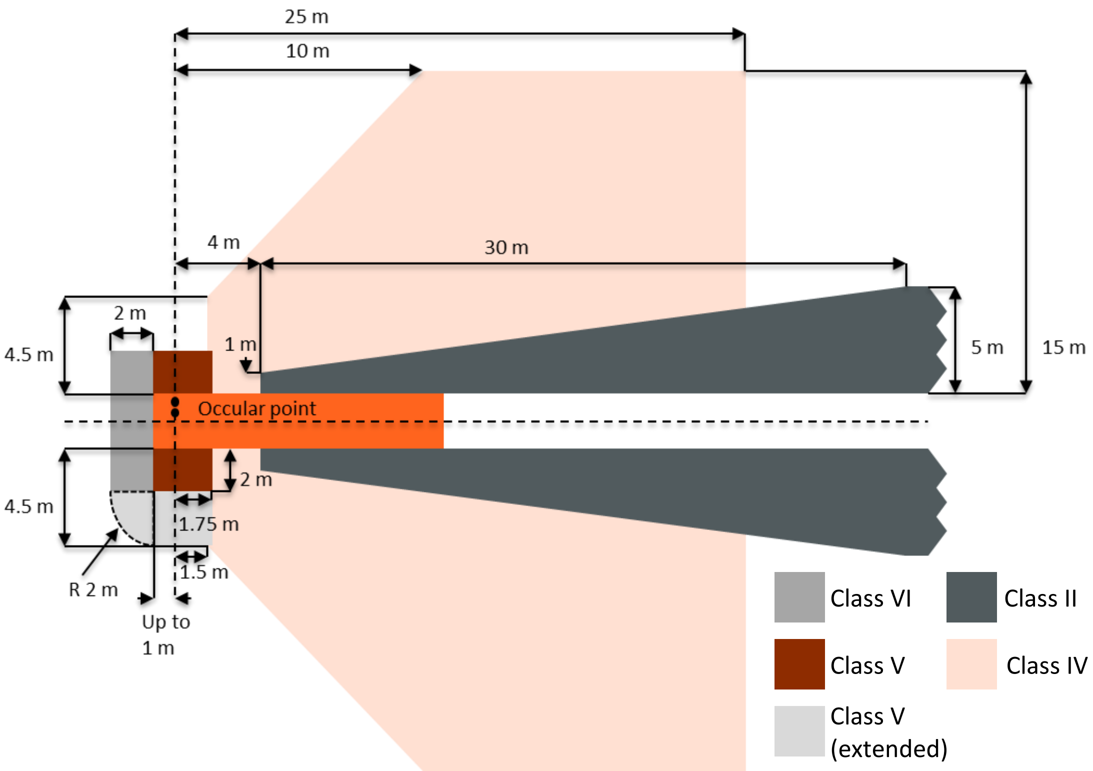


Figure 4: Relevant field of vision zones specified by UN R46 (Indirect Vision Devices). The Class II field of vision zone, in dark grey, is the only zone mandated for M3 category vehicles such as city buses

2.4.2 Key driver fields of vision

For each of the four safety measures, it is necessary to identify the key driver fields of vision which the VRU casualty may have passed through prior to collision with the bus. Figure 5 illustrates the key driver fields of vision and Table 3 defines these zones in terms of the movement of the bus and VRU and the impact points.

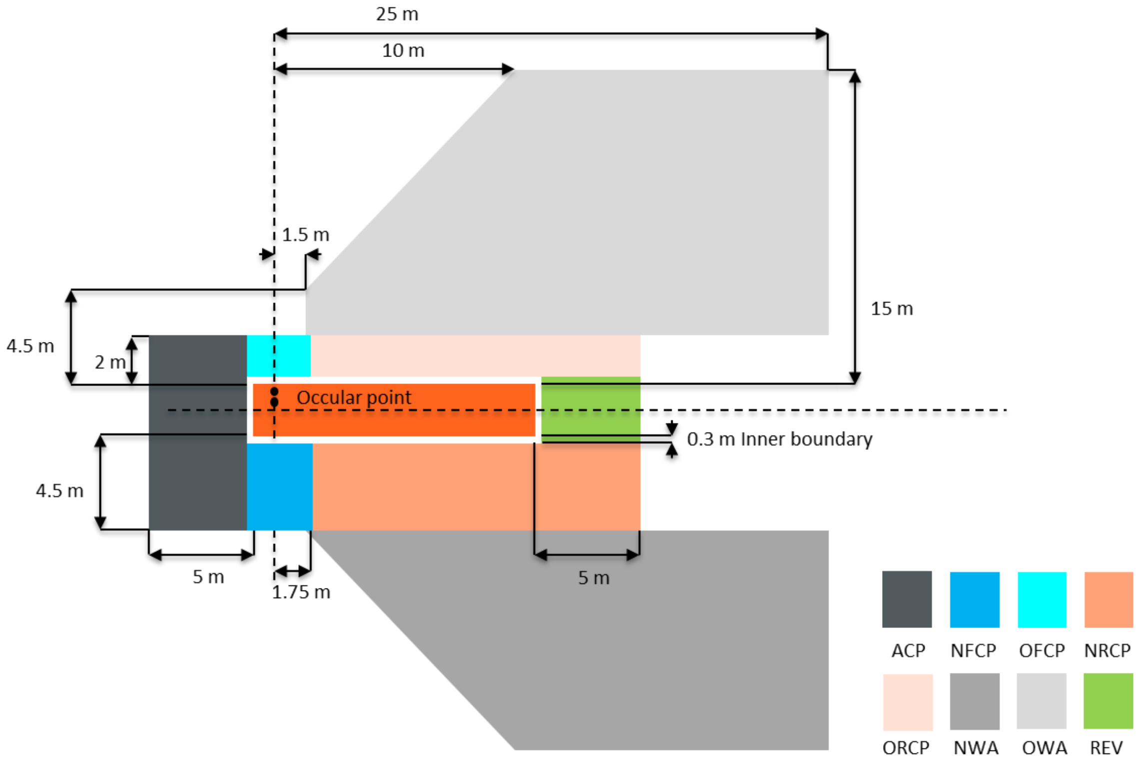


Figure 5: Key field of vision categories for bus drivers, when considering relevant VRU to bus collision characteristics

Table 3: Collision characteristics associated with specific fields of vision and defined by vehicle/VRU manoeuvre and first vehicle/VRU impact point

Field of Vision Category	VRU Category	Vehicle Manoeuvre	Vehicle Impact	VRU Manoeuvre	VRU Impact
Advanced Close-Proximity Field of Vision (ACP)	Pedestrian	1) Slowing/stopping 2) Moving off 3) U-turn 4) Turning left/right	Front	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	1) Slowing/stopping 2) Moving off 3) U-turn 4) Turning left/right	Front	1) Waiting to turn right/left 2) Waiting to go – held up 3) Turning right/left 4) Slowing or stopping 5) Moving off	All
Nearside Forward Close-Proximity Field of Vision (NFCP)	Pedestrian	1) Slowing/stopping 2) Moving off 3) U-turn 4) Turning left/right	Forward Aspect of Nearside (79%)*	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	1) Slowing/stopping 2) Moving off 3) U-turn 4) Turning left/right	Forward Aspect of Nearside (79%)*	1) Waiting to turn right/left 2) Waiting to go – held up 3) Turning right/left 4) Slowing or stopping 5) Moving off	Offside
Offside Forward Close-Proximity Field of Vision (OFCP)	Pedestrian	1) Slowing/stopping 2) Moving off 3) U-turn 4) Turning left/right	Forward Aspect of Offside (75%)†	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	1) Slowing/stopping 2) Moving off 3) U-turn 4) Turning left/right	Forward Aspect of Offside (75%)†	1) Waiting to turn right/left 2) Waiting to go – held up 3) Turning right/left 4) Slowing or stopping 5) Moving off	Nearside
Nearside Rearward Close-Proximity Field of Vision (NRCP)	Pedestrian	1) Overtaking on offside 2) Slowing/stopping 3) Moving off 4) U-turn 5) Turning left/right	Rearward Aspect of Nearside (21%)*	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	1) Overtaking on offside 2) Going ahead left/ right bend/other 3) Slowing/stopping 4) Moving off 5) U-turn 6) Turning left/right	Rearward Aspect of Nearside (21%)*	1) Overtaking on nearside/offside 2) Going ahead left/ right bend/other 3) Waiting to turn right/left 4) Waiting to go – held up 5) Turning right/left 6) Slowing or stopping 7) Moving off	Offside

Field of Vision Category	VRU Category	Vehicle Manoeuvre	Vehicle Impact	VRU Manoeuvre	VRU Impact
Offside Rearward Close-Proximity Field of Vision (ORCP)	Pedestrian	1) Overtaking on nearside 2) Slowing/stopping 3) Moving off 4) U-turn 1) Turning left/right	Rearward Aspect of Offside (25%)†	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	1) Overtaking on nearside 2) Going ahead left/ right bend/other 3) Slowing/stopping 4) Moving off 5) U-turn 1) Turning left/right	Rearward Aspect of Offside (25%)†	1) Overtaking on nearside/offside 2) Going ahead left/ right bend/other 3) Waiting to turn right/left 4) Waiting to go – held up 5) Turning right/left 6) Slowing or stopping 7) Moving off	Nearside
Nearside Wide Angle Field of Vision (NWA)	Pedestrian	1) Changing lane to left	Nearside	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	1) Changing lane to left	Nearside	1) Overtaking on nearside/offside 2) Going ahead left/ right bend/other 3) Waiting to turn right/left 4) Waiting to go – held up 5) Turning right/left 6) Slowing or stopping 7) Moving off	Offside
Offside Wide Angle Field of Vision (OWA)	Pedestrian	1) Changing lane to right	Offside	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	1) Changing lane to right	Offside	1) Overtaking on nearside/offside 2) Going ahead left/ right bend/other 3) Waiting to turn right/left 4) Waiting to go – held up 5) Turning right/left 6) Slowing or stopping 7) Moving off	Nearside
Reversing Field of Vision (REV)	Pedestrian	Reversing	Rear	1) Crossing from driver nearside/offside 2) Stationary in carriageway 3) Walking along facing/back to traffic	N/A
	Cyclist/PTW	Reversing	Rear	All	All

* Factor based on proportion of VRU collisions impacting the foremost aspect of the nearside of bus/coaches, relative to the entire nearside, from Knowles et al. (2012)

† Factor based on proportion of VRU collisions impacting the foremost aspect of the offside of bus/coaches, relative to the entire offside, from Knowles et al. (2012)

2.5 Casualty analysis

The STATS19 database was analysed to identify the number of casualties occurring annually in Greater London (including Heathrow) between 2006-2015 and where the casualty may have passed through the key driver fields of vision. The relevant target population for each DIV safety measure was determined using a combination of key driver field of vision zones for each of the four functional categories (Direct Vision (DIR), Indirect Vision (IND), Internal Obscurations (IOB) and VRU Detection (DET)). The following sub-sections therefore define which field of vision zones relate to each functional category and provide a breakdown of annual casualty numbers for each VRU category and each severity level.

2.5.1 Direct vision (DIR) and internal obscurations (IOB)

Casualties that may be prevented through improving the driver's direct vision primarily travel through the driver's forward fields of vision. These include the Advanced, Nearside Forward and Offside Forward Close-Proximity field of vision zones (ACP, NFCP and OFCP). For the following analysis these three zones have been combined into a new "Forward Close-Proximity (FCP)" field of vision zone that is specifically relevant to the driver direct vision problem addressed by the DIR and IOB safety measures. Table 4 details the target population for the FCP field of vision zone, illustrating that pedestrians are the most affected VRU involved in bus collisions when manoeuvring through the FCP field of vision zone.

Table 4: Estimated number of VRU casualties from collisions involving single buses/coaches in London between 2006 and 2015 relevant to the Forward Close-Proximity (FCP) field of vision zone (data source: STATS19)

Field of Vision	Casualty Type	Injury Severity		
		Fatal	Serious	Slight
ACP	Pedestrian	19.0	73.0	351.0
	Cyclist	1.0	4.0	47.0
	PTW	0.0	1.0	25.0
NFCP	Pedestrian	6.3	45.0	158.8
	Cyclist	0.0	4.7	40.3
	PTW	0.0	0.8	7.9
OFCP	Pedestrian	0.8	9.0	29.3
	Cyclist	0.0	2.3	15.0
	PTW	0.0	0.0	12.0
FCP	**Pedestrian**	**26.1**	**127.0**	**539.0**
	Cyclist	**1.0**	**11.0**	**102.3**
	PTW	**0.0**	**1.8**	**44.9**

Pedestrians involved in collisions relating to the direct vision of the bus driver comprise 24% of all pedestrian fatalities, 16% of all pedestrian serious injuries and 18% of all pedestrian slight injuries. Cyclist and PTW injuries, however, represent a much smaller proportion of their respective total casualty populations at each injury severity level

(<12.5%). It may therefore be concluded from this information that a key priority must be to address the pedestrian casualties relevant to the direct vision of the driver.

For the FCP field of vision zone, it was estimated that the majority of VRU collisions with buses occurred when pedestrians manoeuvred through the ACP zone (64%), followed by pedestrians manoeuvring through the NFCP zone (30%). Although cyclists account for a smaller proportion of casualties relating to direct vision, they were also involved in collisions when primarily manoeuvring through the ACP (45%) and NFCP (39%) zones. As PTWs were not as affected as pedestrians and cyclists, numbers were too small to make reasonable conclusions about where the problem existed.

The reasons for this trend in the collision landscape may be from a combination of the positioning of the driver in the bus and the typical manoeuvres made by VRUs when moving in close proximity to a bus. As the driver is seated on the offside of the bus, this provides a better field of view to the driver of any hazards to the offside of the bus. External and internal obstructions (e.g. bodywork, A-pillars, wing mirrors, driver assault screens) may therefore be obscuring the driver's view of hazards in the road ahead and to the nearside. VRUs, and in particular pedestrians, do not typically manoeuvre themselves around the offside of a bus, reducing the exposure of VRUs to this type of collision characteristic. Further research is, therefore, needed to better determine the extent of any obscuration and establish appropriate solutions. This further research is provided in Sections 6.2 and 6.3, which respectively define the direct vision performance of current bus designs and the impact that internal obscurations have on direct vision performance.

2.5.2 Indirect Vision (IND)

Casualties that may be prevented through improving the indirect vision of the driver primarily travel through the driver's rearward fields of vision. These include the Nearside/Offside Rearward Close-Proximity, Nearside/Offside Wide-Angle and Reversing field of vision zones (NRCP, ORCP, NWA, OWA and REV). For an analysis considering VRUs in close proximity of the bus, then the NRCP, ORCP and REV have all been combined into a new "Rearward Close-Proximity (RCP)" field of vision zone. Similarly, the NWA and OWA field of vision zones have been combined into a new "Rearward Wide-Angle (RWA)" field of vision zone for analysis of collisions where the VRU was not as close to the vehicle.

Table 5 shows the total target populations for each rearward field of vision zone and the combined target populations for the RCP and RWA field of vision zones. This shows that, for cyclists and PTWs, the rearward field of vision zones are more important than the forward field of vision zones for the prevention of VRU casualties, due to the larger number of casualties in the RCP field of vision zone.

Table 5: Estimated number of VRU casualties from collisions involving single buses/coaches in London between 2006 and 2015 relevant to the rearward field of vision zones (data source: STATS19)

Field of Vision	Casualty Type	Injury Severity Fatal	Serious	Slight
NRCP	Pedestrian	1.7	12.0	46.2
	Cyclist	2.0	21.3	173.7
	PTW	1.0	3.2	32.1
ORCP	Pedestrian	0.3	3.0	10.8
	Cyclist	0.0	7.8	57.0
	PTW	1.0	8.0	78.0
REV	Pedestrian	1.0	0.0	4.0
	Cyclist	0.0	0.0	1.0
	PTW	0.0	0.0	2.0
RCP	**Pedestrian**	**2.9**	**15.0**	**61.0**
	Cyclist	**2.0**	**29.0**	**231.7**
	PTW	**2.0**	**11.2**	**112.1**
NWA	Pedestrian	0.0	0.0	1.0
	Cyclist	0.0	5.0	43.0
	PTW	0.0	2.0	8.0
OWA	**Pedestrian**	**0.0**	**0.0**	**0.0**
	Cyclist	0.0	1.0	9.0
	PTW	0.0	0.0	15.0
RWA	**Pedestrian**	0.0	**0.0**	**1.0**
	Cyclist	0.0	**6.0**	**52.0**
	PTW	0.0	**2.0**	**23.0**

Cyclists involved in collisions relating to the close-proximity indirect vision of the bus driver comprise 25% of all cyclist fatalities, 16% of all cyclist serious injuries and 21% of all cyclist slight injuries. These results were replicated for collisions involving PTWs, with 29% of PTW fatalities, 13% of PTW serious injuries and 22% of PTW slight injuries relating to the close-proximity indirect vision of the bus driver. These represent a considerably higher proportion of the total casualties for these VRU casualty types when compared to the proportion of casualties associated with the direct vision of bus drivers. It may therefore be concluded that improvements to the close-proximity indirect vision of drivers may potentially address a large proportion of cyclist and PTW casualties involved in collisions with buses.

Pedestrians in collisions relating to the RCP indirect vision of the bus driver represent a much smaller proportion of the total number of pedestrian casualties at each injury severity level (<3%). Despite being a lower proportion of all pedestrian casualties, the absolute number of pedestrian casualties is not entirely insignificant when compared to the other types of VRU, particularly as pedestrians are the leading VRU for fatalities relating to the RCP field of vision. When compared to the direct vision problem, however, it may be concluded that pedestrian casualties relevant to the direct vision of the driver are the higher priority.

When considering the most important field of vision zones for each VRU casualty type, it is clear to see a number of key differences in the collision characteristics associated with each VRU. Over three times as many cyclists were injured when manoeuvring through the NRCP field of vision zone, when compared to manoeuvring through the

ORCP zone. This difference was even greater for pedestrians, where over four times as many pedestrians were injured when manoeuvring through the NRCP field of vision zone, when compared to the ORCP zone. Conversely, however, over twice as many PTWs were injured whilst manoeuvring through the ORCP zone when compared to the NRCP zone.

These differences are likely to be due to the types of manoeuvres being performed by the VRU and bus prior to the collision. Pedestrians may be stepping off pavements toward the nearside of the bus and cyclists may be either undertaking buses on it’s nearside or being overtaken by buses on their offside. PTWs, however, are more likely to be overtaking the bus on it’s offside. When considering the NWA, OWA and REV field of vision zones, it is clear to see that there is a significantly lower number of VRU casualties involved in collisions when manoeuvring through these field of vision zones. It is therefore important that these key differences in collision characteristics are used to prioritise the most important collision characteristics for the BSS.

2.5.3 VRU detection (DET)

Casualties that may be prevented through the use of sensor-based VRU detection systems used to improve driver awareness of VRUs in close-proximity to the bus can travel through all close-proximity driver fields of vision. Each system will, however, have a specific field of vision relative to the direction that it can detect VRUs. Thus, the NFCP and NRCP field of vision zones have been combined into a new “Nearside Close-Proximity (NCP)” field of vision zone for nearside facing VRU detection systems, whilst the OFCP and ORCP field of vision zones have been combined into a new “Offside Close-Proximity (OCP)” field of vision zone for offside facing VRU detection systems. Finally, forward facing detection systems used the ACP field of vision zone and rearward facing detection systems used the REV field of vision zone.

Table 6 shows the total target populations for each relevant field of vision zone and the combined target populations for the NCP and OCP field of vision zones. This shows that the ACP and NCP field of vision zones are more important than the OCP and REV field of vision zones for the prevention of VRU casualties, due to the larger number and severity of casualties involved in collisions with buses in these zones.

Table 6: Estimated number of VRU casualties from collisions involving single buses/coaches in London between 2006 and 2015 relevant to the VRU detection system field of vision zones (data source: STATS19)

Field of Vision	Casualty Type	Injury Severity		
		Fatal	Serious	Slight
NFCP	Pedestrian	6.3	45.0	158.8
	Cyclist	0.0	4.7	40.3
	PTW	0.0	0.8	7.9
NRCP	Pedestrian	1.7	12.0	46.2
	Cyclist	2.0	21.3	173.7
	PTW	1.0	3.2	32.1
NCP	**Pedestrian**	**8.0**	**57.0**	**205.0**
	Cyclist	**2.0**	**26.0**	**214.0**
	PTW	**1.0**	**4.0**	**40.0**
OFCP	Pedestrian	0.8	9.0	29.3
	Cyclist	0.0	2.3	15.0
	PTW	0.0	0.0	12.0
ORCP	Pedestrian	0.3	3.0	10.8
	Cyclist	0.0	7.8	57.0
	PTW	1.0	8.0	78.0
OCP	**Pedestrian**	**1.0**	**12.0**	**40.0**
	Cyclist	**0.0**	**10.0**	**52.0**
	PTW	**1.0**	**8.0**	**23.0**
ACP	**Pedestrian**	**19.0**	**73.0**	**351.0**
	Cyclist	**1.0**	**4.0**	**47.0**
	PTW	**0.0**	**1.0**	**25.0**
REV	**Pedestrian**	**1.0**	**0.0**	**4.0**
	Cyclist	**0.0**	**0.0**	**1.0**
	PTW	**0.0**	**0.0**	**2.0**

VRUs involved in collisions relating to the advanced close-proximity zone of the bus, comprise 16% of all VRU fatalities, 7% of all VRU serious injuries and 9% of all VRU slight injuries. A lower proportion of fatalities were experienced by VRUs involved in collisions relating to the nearside close-proximity zone of the bus, which comprised of 9% of all VRU fatalities, 8% of all VRU serious injuries and 10% of all VRU slight injuries. When considering both the offside close-proximity and reversing zones, neither zone comprised of >3% of the total VRU casualties at any injury severity level.

When comparing the ACP and NCP field of vision zones, it is clear to see a number of key differences in the collision characteristics associated with each VRU. Over four times as many cyclists were injured when manoeuvring through the NCP field of vision zone than when compared to manoeuvring through the ACP zone. This trend was reflected by PTWs, where PTWs experienced 1.7 times as many injuries when manoeuvring through the NCP zone. For pedestrians, however, this relationship was reversed, with over 1.6 times as many pedestrians injured manoeuvring through the ACP when compared to manoeuvring through the NCP. Importantly, this difference in pedestrian collision characteristics is further increased when considering fatalities only, where over twice as many pedestrians are killed whilst manoeuvring through the ACP when compared to manoeuvring through the NCP.

The reasons for these trends are primarily linked to the types of manoeuvres that the VRUs are performing in close-proximity to the bus. Pedestrians are more likely to be crossing in front of the bus, whilst cyclists are more likely to be either passing a bus on its nearside or being overtaken by a bus on their offside. When considering the OCP and the REV field of vision zones, it is clear to see that there is a significantly lower number of VRU casualties injured when manoeuvring through these zones. It is therefore important that the differences in collision characteristics are used to prioritise the most important collision characteristics for the BSS.

2.6 Summary of Target Populations

Using the data described in Section 2.5, the annual top-level target populations were estimated for all casualty severities relevant to the direct vision (DIR) and internal obscuration (IOB) safety measures (fatal, serious and slight casualties) and are presented in Table 7. These top-level target populations were considered to be equivalent between the DIV and IOB safety measure solutions. Further refinement to the target population of the internal obscuration safety measure, based on providing a more relevant target population for that particular measure, is described in Sections 6.3 and 7.1.

Table 7: Estimated average annual top-level target populations for the direct vision (DIV) and internal obscuration (IOB) safety measure solutions (data source: STATS19)

Casualty Type	Outcome Severity Fatal Casualties	 Serious Casualties	 Slight Casualties
Pedestrians	2.6	12.7	53.9
Cyclists	0.1	1.1	10.2
PTWs	0	0.2	4.5
Totals	**2.7**	**14.0**	**68.6**

The annual top-level target populations estimated for all casualties relevant to the indirect vision (IND) safety measure (fatal, serious and slight casualties) are presented in Table 8. Further refinement to the target population for each safety measure solution, based on providing a more relevant target population to the particular solution, is described in Section 7.1.

Table 8: Estimated average annual top-level target populations for the indirect vision (IND) safety measure solutions (data source: STATS19)

Casualty Type	Outcome Severity Fatal Casualties	 Serious Casualties	 Slight Casualties
Pedestrians	0.3	1.5	6.2
Cyclists	0.2	3.5	28.3
PTWs	0.2	1.3	13.4
Totals	**0.7**	**6.3**	**47.9**

The annual top-level target populations estimated for all casualties relevant to the VRU detection (DET) safety measure (fatal, serious and slight casualties) are presented in Table 9. Further refinement to the target population for each safety measure solution, based on providing a more relevant target population to the particular solution, is described in Section 7.1.

Table 9: Estimated average annual top-level target populations for the VRU detection (DET) safety measure solutions (data source: STATS19)

Casualty Type	Outcome Severity		
	Fatal Casualties	Serious Casualties	Slight Casualties
Pedestrians	2.7	13.0	55.6
Cyclists	0.3	3.0	26.1
PTWs	0.1	0.5	6.5
Totals	**3.1**	**16.5**	**88.2**

3 Examples of solutions

3.1 Introduction

The purpose of this section is to review the range of technologies and approaches available as potential solutions for the Direct and Indirect Vision (DIV) safety measure. This will be achieved by summarising the range of relevant technologies and approaches for direct vision, mirrors, camera monitoring systems and blind spot warning systems. The potential solutions summarised by this review are mainly used on heavy goods vehicles, with these used to provide background information on the future DIV safety measure solutions that could be implemented by the Bus Safety Standard (BSS).

3.2 Direct vision

Over many years, driver blind spots have been identified as a contributory factor in collisions involving HGVs. The direct vision through the glazed areas of HGVs is such that, given their height from the ground, pedestrians and cyclists may be easily hidden in many areas that cannot be seen directly and in some areas that cannot be seen either directly or indirectly through the available mirrors.

The direct vision of buses is far superior to that from most HGVs, although fewer mirrors are required on buses, such that the indirect field of view is considered to be inferior. Generally, the blind spots surrounding the front end of buses are smaller; however, collisions involving pedestrians and cyclists that are either killed or seriously injured, when positioned in close proximity to a moving bus, do still occur.

Typically, direct vision blind spots in buses are not located in areas where vulnerable road users will be obscured by the lower edge of the windscreen. Instead, potential obstructions to driver visibility are typically caused by the A-pillars of the bus, the pillars around and at the centre of the front doors, the driver assault screen and by equipment in the driver cabin.

A key solution to this issue currently under development is the TfL HGV Direct Vision Standard (DVS). This lays out a standardised testing and assessment procedure to measure the direct field of vision of HGV drivers to ensure that HGV designs provide a minimum level of direct vision performance. More information on the TfL HGV DVS, and its relevance to buses, is provided in Section 5.1.5.

3.3 Mirrors

In addition to direct vision, blind spots can be mitigated using Class II, Class IV, Class V and Class VI mirrors which provide indirect vision of the space around the vehicle.

All new vehicles sold in the EU from January 2007 have had to comply with Directive 2003/97/EC which substantially increased the size of the minimum field of view from mirrors. In addition to this, Directive 2007/38/EC required that the class V blind spot mirror at the nearside, as defined by Directive 2003/97/EC, should be retrofitted to existing HGVs on the road that were not already equipped. Continuing improvements to indirect vision have been implemented in type approval through UN Regulation 46

(UN R46) with an additional change to blind spot mirror requirements coming into force in 2016 to increase the size of the required ground plane field of view (Figure). As previously noted in section 2.4.1, only the Class II field of vision zone is mandated for M3 category vehicles (buses/coaches). This has resulted in the vast majority of city buses being fitted with standard planar Class II “wing mirrors”. This means that the safety benefits of other fields of view may not be being realised.

In a mirror of fixed and relatively small dimensions (compared to the total of human peripheral vision) the object the driver needs to detect is a small image and the amount by which that image can move across the mirror is also small (Schmidt, et al., 2015). Thus, it is less likely to attract the attention of the driver in the same way as it would if it was visible at life size in a direct field of view where it would move across a much larger proportion of the peripheral view. For mirrors to be effective, the driver must have a conscious, trained, strategy of scanning the mirrors at key moments and this takes a finite amount of time.

(Schmidt, et al., 2015) states that when using mirrors, it can be difficult for drivers to accurately estimate distance and speed and that high speeds are typically underestimated but slow speeds typically overestimated. The ability to show depth of vision in mirrors is also limited. The human brain can learn to compensate for this (Schmidt, et al., 2015) but the visual cues that enable this compensation will also be complicated by the visual distortion that comes from a curved mirror. In these circumstances, the brain must work harder to compensate for the curvature. Thus UN R46 has evolved to limit the curvature of mirrors, to maximise image size and minimise distortion.

Mirrors are by necessity adjustable such that they can provide the correct field of view for drivers of different statures and in different seating positions. However, this also leaves the opportunity for mirrors to be poorly adjusted such that they do not provide the field of view that they are supposed to. For example, (Fenn, et al., 2005) cited research showing that less than half of 2,000 HGVs surveyed had correctly adjusted mirrors and (Schoon, 2009) showed that in 37% of collisions involving blind spots, mirrors were poorly adjusted. (Fenn, et al., 2005) showed that in a stated preference survey, most HGV drivers self-reported that they did use close-proximity mirrors for their intended purpose most of the time. However, a significant minority admitted to rarely or never adjusting them when they got in the cab (11%) and to rarely or never using the mirrors to check for cyclists or pedestrians by the nearside door when undertaking low speed manoeuvres (14%).

The Ashtree Vision & Safety Ltd CycleSafe mirror (Figure 6) is an example of a product that is currently in use that can provide the driver with a greater Field of View than the mandated Class II requirements (Ashtree Vision & Safety Ltd, 2019). Using this device, a driver can see areas surrounding the vehicle which fall within the Class IV and Class V ground planes.

Figure 6: Ashtree CycleSafe mirror

3.4 Camera Monitor Systems (CMS)

According to UN R46, a Camera Monitor System (CMS) is defined as a device which represents the field of vision obtained by the driver though the means of a camera and monitor combination. CMS are used in vehicles to provide the driver with information on a specific field of vision (usually the rear view). The most common applications include:

- **Supplementary indirect vision**: CMS as an indirect view over and above those defined by UN R46: Some views, such as the view immediately behind a vehicle, are almost impossible to see with mirrors. Others are difficult without increasing size of mirrors or their curvature, each of which have significant disadvantages.
- **Mirror replacement**: CMS replacing one or more of the indirect views required by UN R46: Replacing mirrors with cameras can reduce obstructions to direct vision, reduce aerodynamic drag and reduce the cost of frequent damage to mirrors as well as occasional injuries where mirrors collide with pedestrians.
- **360-degree birds-eye view CMS**: Where the views from multiple cameras are synthesised into a single plan view image of the vehicle and objects around it.

Using cameras rather than mirrors means that the external object can be smaller and, without the need for direct line of sight between the driver's eyes and the mirror, the camera can be optimally positioned to provide the best coverage. Similarly, the monitor used by the driver can also be in the most intuitive position and/or to minimise any blind spot behind it.

The key consideration for the fitment of CMS is whether it makes it easier or harder for driver to scan surroundings and identify threats. CMS fitted in addition to mandatory mirrors has the potential to increase driver workload, simply by creating additional areas that must be scanned. Additionally, poor quality images would also increase the time required to process and understand them. Conversely a well-designed system replacing mirrors with monitors in intuitive locations offering clear and easily interpreted images could have the opposite effect and reduce a driver's workload.

(Milner & Western-Williams, 2016) reviewed literature and found several risks related to using monitors aimed at extending HGV vision while driving:

- Increased periods of off-road glances;
- Drivers take longer to acquire critical information when returning their gaze to the road;
- The image resolution is sensitive to environmental conditions;
- Limited resolution and colour range, introduces a time delay, although minimal;
- Increased workload to process additional visual information; and
- Processing the spatial location of the visual information received (e.g. where is a pedestrian seen in a monitor in relation to the vehicle).

The potential consequences of these risks are:

- Reduced hazard detection;
- Abrupt steering wheel movements; and
- Impaired lane keeping.

To demonstrate the technical feasibility of CMS systems, the following subsections provide a number of examples of production-ready CMS systems.

3.4.1 MirrorEye™

MirrorEye replaces standard external mirrors with camera units, positioned against the side of the body of the bus. The Orlaco website reports that the design of the MirrorEye camera units is universal and only the interface between the camera units and the body of the bus or coach is vehicle-specific (Orlaco). Advantages of the system that are cited include a clear image across a variety of weather and lighting conditions, including automatic adjustment for night-time or dark tunnels.

3.4.2 MAN Buses

An article for the Route One website (Deakin, 2018) reported that MAN was fitting cameras to replace mirrors on its range of coaches. The cameras are within small casings mounted where the mirror arms would otherwise meet the body. Each camera is fed to a colour LCD screen on the A-pillar. The article reported that, although it was lacking from the demo vehicle, production installations were expected to include a camera above the windscreen that faces downwards to give a view of frontal obstructions.

(Deakin, 2018) highlighted that, should a camera or a screen fail, MAN provides two basic mirror arms to be kept aboard the coach that can be attached easily. Based on a small fuel saving from reduced wind resistance and reduced parts costs for replacement mirrors, MAN suggested a payback period of three years.

3.4.3 Continental ProViu®Mirror

ProViu®Mirror CMS (continental) is aimed at HGV's, coaches and agricultural tractors. It utilises two cameras installed at different angles, on each side of the vehicle, to expand the driver's indirect field of vision. The feed is displayed on 12-inch split screen monitors positioned internally on the vehicles A-pillars. In comparison to conventional wing mirrors the necessity for head movements of the operator is clearly reduced.

3.5 Blind spot information, warning and intervention systems

The use of sensing systems to detect the presence of vulnerable road users and warn drivers can have several advantages:

- Small unobtrusive sensors can see a wide field of view and can fill blind spots left between direct and indirect vision;
- Warnings can draw the attention of a driver to a problem even if the driver is not looking in the right direction; and
- Sensors can monitor different areas of view simultaneously, which humans cannot do with mirror views and only partially via peripheral vision for direct views through the windscreen.

Thus, blind spot information, warning and intervention systems can be of benefit in terms of eliminating blind spots and improving the chances of a driver detection of vulnerable road users where they may already be visible via direct or indirect vision. This is particularly true in highly dynamic collision types where, for example:

- A cyclist is at a substantial distance from the vehicle when a driver initially checks the mirror and sees the cyclist in the N/S class II mirror;
- The cyclist moves forward rapidly;
- The next time the driver scans the nearside mirrors, the cyclist may be moving between the visibility zones of the class V blind spot mirrors and direct vision, spending only a short time in each;
- The driver may be attentive but not see the cyclist as they look at the wrong place at the wrong time.

A good warning system can, therefore, substitute to some extent for poor vision but can also complement and enhance good vision by acting as an aid to the driver in difficult traffic situations.

Even a good warning system still relies on the driver to react quickly and appropriately to the situation and so the possibility for collisions still remains. In certain circumstances it may be possible for the vehicle to intervene on behalf of the driver to prevent a collision that a driver has not reacted appropriately to, despite the warning being issued.

To demonstrate the technical feasibility of blind spot information, warning and intervention systems, the following subsections provide a number of examples of production-ready blind spot warning systems.

3.5.1 *Mobileye Shield +™*

This system comprises of multiple systems covering the area around the bus:

- Pedestrian and Cyclist Collision Warning (Mobileye PCW);
- Forward Collision Warning (Mobileye FCW);
- Headway Monitoring Warning (Mobileye HMW);
- Lane Departure Warning (Mobileye LDW); and
- Speed Limit Indicator (Mobileye SLI).

The system uses image recognition software to reduce unnecessary warnings and is designed to only alert a driver if a collision is imminent with a VRU, not inanimate objects.

In principle, these systems cover the key scenarios in which VRUs and other road users are typically injured; pedestrians or cyclists in impacts to the front/side of buses and collisions between the front of a bus and the rear of another vehicle.

The system uses multiple displays within the cab to alert the driver to potential or imminent collisions.

3.5.2 Fusion Processing – CycleEye®

CycleEye® is a collision avoidance system for HGVs and buses that detects cyclists alongside the vehicle and alerts drivers to their presence (13). The product description suggests that this system is focussed on addressing the blind spot to the nearside of the vehicle and does not address blind spots that can occur to the front or offside of a vehicle.

Figure 13: Fusion Processing – CycleEye® (source: www.fusionproc.com)

The system uses a combination of radar and low light camera sensors and is designed to distinguish cyclists against a background of street furniture and other vehicles.

4 Solution performance

4.1 Introduction

The purpose of this section is to perform a review of the effectiveness of the Direct and Indirect Vision (DIV) safety measure solutions discussed in Section 3. The effectiveness of a safety measure solution is determined by how well the solution performs. Estimates of effectiveness can be calculated based on the percentage of casualties whose death or injury could have been prevented, or injury severity mitigated, should the safety measure solution be implemented across the entire fleet.

The following subsections therefore review the current evidence base underpinning the estimation of effectiveness values for each safety measure solution. A summary of overall effectiveness values is presented in Section 4.8.

4.2 Direct vision

(Milner & Western-Williams, 2016) reported on both survey and experimental studies to assess the effectiveness of direct vision. In experiments where subjects in a stationary vehicle were asked to react to the presence of stimuli in both their direct and indirect fields of vision, their reaction times did not differ. However, when replicated in a driving simulator, the study found that viewing a pedestrian through direct vision, whilst driving, resulted in reaction times on average approximately 0.7 seconds quicker than when viewed in indirect vision. Survey evidence from (Milner & Western-Williams, 2016) also showed that vulnerable road users considered that direct vision would give them more confidence that they had been seen when moving around a large vehicle.

(Knight, et al., 2017) collated comprehensive causation data concerning the number of collisions where blind spots were considered a potential contributory factor in close-proximity manoeuvring collisions between HGVs and vulnerable road users in London. A simple percentage effectiveness was derived based on the experimentation by (Milner & Western-Williams, 2016). In all scenarios a 0-star vehicle (on a scale of zero to five) was considered equivalent to the current fleet (0% effectiveness). Where the HGV was moving off from rest, a 5-star vehicle was estimated to be 77% to 88% effective (i.e. likely to prevent between 77% and 88% of this type of collision). For left turn collisions the effectiveness of a 5-star vehicle was considered to be 19% to 22%. For both scenarios the effectiveness of 1-star to 4-star vehicles was calculated based on linear interpolation between the 0-star and 5-star cases.

(Barrow, et al., 2017) undertook a wide-ranging study of the likely casualty reduction effectiveness of a range of 24 measures that were candidates for inclusion as part of the European Commission's proposed revision of the General Safety Regulation and Pedestrian Safety Regulation. Improved Direct Vision was one of those measures. To evaluate the effectiveness of direct vision a case by case analysis was undertaken based on a sample of in-depth collision data from the Road Accident In-Depth Study (RAIDS) database.

Two standards of direct vision were considered:

- Best in class: For current vehicle designs, this assumed ‘removal of the tallest chassis and adoption of new cabs with improved direct vision through the windshield, passenger door and side windows’.
- High direct vision: This is described as ‘a low forward position cab with much improved glazed areas’.

Whether each standard of vision would prove effective at either avoiding the collision or mitigating its consequences was assessed subjectively by the coder, considering the evidence in the file about the quality of vision from the vehicle, the traffic situation and the attentiveness of the driver. The coders were asked to give their opinion in each case as to whether they had high (67%-100%), medium (34% - 66%), low (1%-33%) or zero confidence in whether the measure would be effective. The results showed a range of effectiveness from 1% to 36% for ‘best in class’ vision and 1% to 48% for ‘high direct vision’. (Barrow, et al., 2017) provide a central estimate (their ‘prediction’) based on counting all cases with high or medium confidence, to produce effectiveness estimates of 3% for the best in class cab and 27% for the high direct vision cab.

A study by ARUP (Wilkie & Mole, 2017) for TfL investigated the implications of mandating direct vision to HGVs. The review highlighted that windscreens and mirrors do not provide a complete view of the entire area surrounding the vehicle, creating blind spots, particularly in the case of HGVs. (Wilkie & Mole, 2017) also identified research which concluded that drivers’ attention is inherently drawn towards VRUs faces. However, they found conflicting evidence regarding whether this natural social interaction enhances safe driving behaviour, or instead delays reaction times, thus compromising safety.

Seeing a pedestrian or cyclist directly through the windows of the vehicle is likely to have several advantages over indirect view through mirrors or camera monitors. The image is full size, free from distortions, substantial movement may be visible (which would help attract the attention of the driver) and direct eye contact is possible between both parties (Robinson, et al., 2016).

(Summerskill, et al., 2015) suggests that lower driver eye-height increases perception of VRUs in close-proximity to the vehicle. (Sahar, et al., 2010) also found that providing drivers with a larger field of view increases hazard detection, thus having the potential to reduce the number of incidents. Importantly, HGV drivers currently heavily rely on mirrors to overcome the restricted direct visual field of the cab, whereas buses typically have better direct field of vision and a lower driving position (Cook, et al., 2011). This means that, through the nature of their design, it would be expected that buses would have a better direct field of vision than the vast majority of HGV designs.

It is clear from this review that previous research has principally focussed on the direct vision problem for HGVs. When considering the direct vision performance of buses, however, it has only anecdotally been noted that buses provide a better direct field of vision to the driver. Similarities clearly exist between the direct vision performance of buses and ‘high direct vision’ HGV cabs (e.g. a low entry cab), given their lower and more forward positioned cab and improved glazed areas. This suggests that bus cabs will similarly provide excellent direct vision to the driver, although no research to date has been performed to confirm this.

As it would be a considerable technical challenge to improve the direct vision of the driver beyond these levels, it is recommended that minimum direct vision requirements are implemented to ensure that future bus designs do not have a reduction in direct vision performance below this baseline level. Although this would mean there would be no expected improvements in casualty outcomes resulting from the implementation of such a measure, it would mean that future bus front end designs do not introduce greater blind spot zones. Further research was therefore performed in Section 6.2 to quantify the current direct vision performance of buses throughout the fleet.

4.3 Indirect vision

4.3.1 Mirrors

Many studies have measured the physical view from vehicles and have found that adding mirrors can substantially increase the view and reduce blind spots. However, no experimental evidence has been identified that attempts to realistically correlate the size and quality of mirror view with correct observation, detection and collision avoidance in the way that (Milner & Western-Williams, 2016) did for direct vision.

(Schoon, 2009) recorded a 43% reduction in the number of relevant deaths in the 2 years after implementing an additional blind spot mirror requirement (at the start of 2002) but this largely disappeared again by 2004 (Figure).

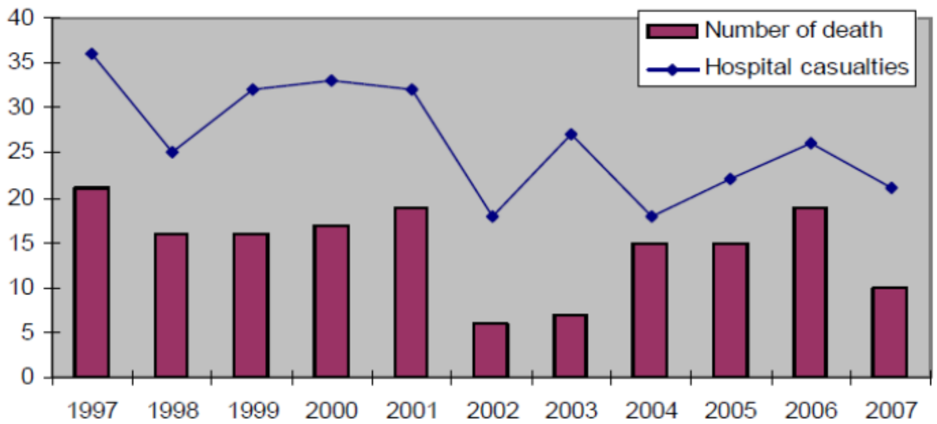


Figure 14: Number of cyclist deaths and casualties in collision

The technical requirement imposed in The Netherlands was to use a specific additional mirror that effectively brought forward in time a large part of the increase in mirror field of view that was required for new vehicles from 2007 by Directive 2003/97/EC.

(Knight, 2011) analysed the CARE (Community database on Accidents on the Roads in Europe) database and showed that there was a generally reducing trend for left turn (right turn in mainland Europe) collisions involving vulnerable road users over the period that the new Directives for HGV mirrors were introduced. However, it also showed collisions of all types reduced by a comparable amount in the same period and that the reduction in left turn collision was small compared to a much bigger reduction in collisions when the HGV was moving straight ahead. Thus, the proportion of all VRU fatalities from collisions involving HGVs turning left had increased from 16% to 24%. The conclusion of the study was that the reductions in casualty numbers seen exceeded predictions of the effect of the retrofit directive but that there was little evidence to prove that the retrofit of blind spot mirrors had caused this reduction, or even part of it.

(Thomas, et al., 2015) found that of 27 London HGV-cyclist collisions studied in detail, mostly involving left turn collisions, all collisions involving a cyclist positioned in a zone relevant to class V mirrors involved HGVs equipped with class V mirrors. This does not necessarily prove that such mirrors are ineffective, they may have been effective in other near collisions that did not occur. However, it does prove that Class V mirrors do not eliminate collisions. For collisions where cyclists were in a position relevant to the class VI frontal mirror, slightly more than half of the vehicles were not equipped with the frontal mirror. This does allow for the possibility of a greater effect for Class VI mirrors but may also be a simple function of exposure: that is, at the time of the collisions far fewer HGVs were equipped with class VI mirrors than class V.

No definitive reason was found for the failure of the driver to see and react to the cyclist in those cases where mirrors should have provided a view. Observations identified from witness statements and analyses included:

- Drivers citing the demands of a busy traffic environment;
- Drivers looking at the mirrors but failing to see the cyclist;
- Relative movement of the cyclist combined with mirror curvature meaning the cyclist would only have been visible in the mirror for a short time;
- Incorrect mirror adjustment; and
- Incorrect understanding of the purpose of the mirrors.

(Fenn, et al., 2005) studied collisions involving HGVs in the Heavy Vehicle Crash Injury Study (HVCIS) fatal accident database. This involved the detailed study of police fatal collision reports for more than half of UK collisions involving HGVs and the routine coding of countermeasures based on a probability scale, subjectively assessed by the coder. This study predicted that as many as 55% of those cyclists killed in collision with an HGV turning left could be prevented. However, it should be noted that the terms of this study were an assessment of improved field of view generally rather than particular design of mirror specifically. As such, coders would have assumed that the ‘improvement’ in vision would have been sufficient to make the cyclist available to be seen and then the probability of avoidance would have depended on whether the evidence suggested the driver involved had properly adjusted their mirror and was or was not paying proper attention at the time of the manoeuvre. Coders would not have had sufficient information to be able to fully assess the likelihood of detection based on the interaction of mirror properties and human visual behaviour, driver workload etc.

(Wilkie & Mole, 2017) summarised previous reports and academic investigations that highlighted a number of risks to relying on mirrors for safe driving, including:

- Recognition rates are compromised towards mirror edges (Cook, et al., 2011);
- Mirrors may be set up incorrectly, impairing areas covered (Cook, et al., 2011);
- Mirrors can distort reflected objects (Sareen, et al., 2014);
- Reflected objects tend to be overlooked in comparison to direct objects (Sareen, et al., 2014) ; and
- View can be influenced by elements such as rain and dirt (Cook, et al., 2011).

Consequently, (Wilkie & Mole, 2017) reported that processing indirect visual information impaired driver performance through:

- Reduced hazard detection (Lee, et al., 2007);
- Abrupt steering wheel movements (Liang & Lee, 2010); and
- Impaired lane-keeping (Wilschut, et al., 2008).

Whilst this research provides an interesting background to the potential effectiveness of mirror-based solutions, there is a paucity in research that specifically quantifies the casualty saving benefits that installing a particular mirror would have. Due to the lack of a specific on-road or simulator trial evidence base to assess the effectiveness of supplementary mirrors for buses, parallels were sought from relevant human factors research studies. These estimate the changes in workload associated with additional mirrors that differ in terms of image size and distortion. Further consideration of these studies, and the conclusions that may be taken from them regarding the effectiveness of mirror safety measure solutions, is provided in Section 4.7.

4.4 Camera monitor systems

There are very few vehicles on the road with mirror replacement Camera Monitor Systems (CMS) and, as such, no statistical evidence in relation to their effect on collision involvement yet exists. Supplementary CMS providing views in addition to mirrors are on vehicles in significant numbers but still no statistical analyses have been identified in relation to heavy vehicles.

(Wilkie & Mole, 2017) reported that the introduction of visual display units (VDUs), aimed at extending an HGV drivers visual field and aiding their decision making, can potentially introduce several risks related to glancing at VDUs when driving, including:

- Increasing periods of off-road glances (Borowsky, et al., 2012);
- Drivers take longer to acquire critical information when returning their gaze to the road (Borowsky, et al., 2012), (Lee, et al., 2007); and
- Resolution sensitive to environmental conditions. (Kidd & McCartt, 2016).

(Schmidt, et al., 2015) explored a comparison of mirrors and VDUs and considered how these might influence driver identification of hazards, concluding that:

- Drivers perceive stationary objects as being further away when viewed in mirrors, and closer when using a VDU;

- The ability to recognise distant objects was found to decline when using VDUs as opposed to mirrors, as images of objects appeared smaller on the monitor than in the mirror;
- Drivers perceive objects to be moving more slowly when using mirrors; and
- Glance duration at indirect visual information was shorter for a VDU monitor located at the height of the door panel – below the side window, and thus outside of the direct field of view.

(Schmidt, et al., 2015) also concluded that the overestimation of speed and the underestimation of distance when using the VDU seem to have a positive effect on road safety. For example, when using VDUs, drivers overestimated the speed at which a car was moving and underestimated the distance of this from their vehicle. As a result, larger gaps for lane changing were chosen – suggesting an unintentional positive effect on road safety.

(Wilkie & Mole, 2017) also cited research which suggested that indirect vision using mirrors and/or VDUs increases cognitive load through:

- Requiring off-road glances (Engström, et al., 2005); and
- Requiring processing of additional visual information (Engström, et al., 2005)

(Fitch, et al., 2011) undertook a controlled 4-month road trial with 12 drivers of HGVs equipped with camera monitoring systems. Two systems were tested. For each driver and system, the vehicle was driven for one month with the system disabled and three months with it enabled. The 'advanced system' involved the fitment of three monitors, one at each A-pillar near the roof line and one at the centre of the screen near the roof. The second system was a 'standard' commercially available system with one camera each side looking rearward and two in-cab monitors placed on the dashboard either side of the steering wheel. In all cases the test vehicle retained its standard mirrors. Unsurprisingly, in a four-month trial, no collisions were encountered. The researchers instead defined 'safety critical events' but found that the use of the monitors did not reduce the number of safety critical events experienced. A concern based on earlier literature was that the monitors would take attention away from the road. However, it was also found that the amount of time the driver spent looking forward at the road did not change. The authors did find that glances at the CMS were of shorter duration than for convex mirrors, suggesting that the driver extracted the required information from the mirrors more quickly than from convex mirrors.

(Large, et al., 2016) studied the effects of mirror replacement CMS in a simulator trial and found that driver performance improved in terms of reduced decision times, though they cautioned that this may at least be partly down to limitations in the experimental design.

(Schmidt, et al., 2015) and (Terzis, 2016) highlighted several technical aspects that need to be considered when comparing the performance of a CMS and a traditional mirror. These may be found in Table 10.

Table 10: Technical considerations for the comparison of CMS and mirror performance across a range of driving scenarios. Adapted from (Schmidt, et al., 2015) and (Terzis, 2016)

Direct Sunlight/Low Sun:	This can cause blooming of the image and a problem where dynamic range of the camera is not sufficient such that either areas of lower light are under exposed (black) or areas of too much light are over exposed (white). This can affect the images provided to the driver, particularly for objects that are based further away from the camera, but also has the advantage of not causing glare on the driver's eyes.
Field of View:	It was found that blind spots could be reduced but the estimation of the distance and speed of objects is more difficult in this aspherical section of the monitor (left). Depending on design, it may therefore be possible to receive more information about distant objects from a CMS than is possible with mirror systems.
Light/Dark Transition:	It was found that when entering a tunnel, the image on the monitor first turns dark, as the camera sensor is underexposed for a moment but adjusts in under 1 seconds. When leaving a tunnel the reverse happens, with an initial overexposure to the light which results in a blooming effect.
Rain:	In light/normal rain, the protected position of the CMS meant it was better than a mirror which suffered from drops and water streaks on the window. Heavy rain results in a more difficult detection of point light sources in the CMS. Both the mirror and CMS are heavily impaired by splashing and rain drops, however, the colour rendering is more realistic in the CMS due to the better contrast ratio.
Night driving:	Individual head lamps of other vehicles can be recognised both in the mirror and in the CMS. CMS Shows some light flare around the head lamps. Rain can make it harder to identify vehicles and estimate speed.
Snow/fog:	At a low ambient luminance including fogged up side windows and / or droplets on the side mirror, the CMS showed an image that was hardly affected by the weather. With increased snow fall and higher ambient luminance a vehicle with the dipped headlights turned on, merges with the background making CMS worse.
Dropouts/ interference:	Dropouts should not occur. A radio with a 446 MHz frequency caused flickering and dropout, though a mobile phone did not. It is very important to design the individual components of the CMS with appropriate measures that ensure compatibility with electromagnetic influences.

This research again provides an interesting background to the potential effectiveness of CMS solutions, however, there remains a paucity in research specifically quantifying the casualty saving benefits that installing a particular CMS would have. Human factor studies may also be looked at for estimations in the changes in workload associated with replacement or supplementary CMS when considering image sizes and distortion. The conclusions that may be taken from them, regarding the effectiveness of CMS safety measure solutions, is provided in Section 4.7.

4.5 VRU detection

There are situations that are considered desirable for VRU detection systems to activate. Examples include when a pedestrian walks across the front of a stationary bus at a time when the bus intended to move off from rest, or when a cyclist is positioned on the nearside of a bus that is turning left and is on a collision course. If the system does indeed activate in such a situation, it is referred to as a ‘true positive’. However, it is also possible to have ‘false positives’ and both true and false negatives. A basic definition of the concept is shown in Table 11. In the most basic form, true positives and true negatives are always desirable, while false positives or negatives are undesirable.

Table 11: Basic classification of system actions. Adapted from (Martinez & Martinez, 2008) as cited by (Lubbe, 2014)

		Does the system activate?	
		Yes	**No**
Will a collision happen in the absence of intervention?	**Yes**	True Positive	False Negative
	No	False Positive	True Negative

However, the definitions are open to interpretation, mainly in terms of timing. A driver might consider that he or she can see a risk of collision, but the warning came too early at a time when they had perceived the risk but not yet deemed it necessary to act. It might be timely, or it might also be perceived as arriving too late to help avoid a collision. Whether any individual driver considers a warning is premature will depend on their own individual driving characteristics. An aggressive driver who regularly brakes harshly and is used to avoiding hazards relatively late, will have a different interpretation of what is premature compared to an overly cautious driver who rarely brakes hard and typically maintains large gaps to vehicles ahead. Similarly, there is a wide range in human emergency braking performance. For example, (Dodd & Knight, 2007) reported on a driving simulator trial with a group of “normal” drivers. The simulated vehicle was capable of a deceleration of 10 m/s^2 but in emergency events on average the subjects only achieved mean decelerations of 7.5 m/s^2.

A study by (Cicchino, 2017) compared crash involvement rates in police-reported lane-change crashes of all severities and with injuries in 26 U.S. states during 2009-2015 between vehicles with blind spot monitoring and the same vehicle models without the optional system. The study found that crash involvement rates in lane-change crashes of all severities and with injuries were 14% and 23% lower, respectively, among vehicles with blind spot monitoring than those without.

(Cicchino, 2016) analysed the effectiveness of forward collision warnings (FCW) intended to prevent front to rear shunt collisions when fitted to passenger cars. She found that vehicles fitted with FCW had on average 23% fewer police reported collisions where the equipped vehicle struck the rear of another vehicle and this was statistically significant. When only front to rear collisions involving injury were considered the reductions from FCW were only around 6% and were not statistically significant. When FCW was combined with automated emergency braking (AEB) then collision involvement was reduced by 39% and collisions with injuries by 42%.

(Rosen, 2013) similarly calculated the effectiveness of VRU (pedestrian/cyclist) AEB systems to range between 32-58%, depending on the VRU casualty type and the injury severity level (Table 12). This involved simulating a range of six separate AEB systems across a number of collision scenarios and estimating changes in impact speeds (and, thus, injury risk) when compared to a reference driver only system.

Table 12: Effectiveness ranges for each VRU category and injury severity level as estimated by (Rosen, 2013)

	Fatals	Serious
Pedestrians	38-40%	33-34%
Cyclists	42-46%	26-27%

(Naujoks, et al., 2016) found that drivers reacted significantly more quickly to hazards with a collision warning system even when that system was not perfectly reliable and gave some false or unnecessary warnings. (Maltz & Shinar, 2004) also found that even ‘imperfect’ collision warnings could aid drivers in the form of a training aid. That is, a frequently issued warning tended to encourage drivers to drive more defensively so that they triggered the warning less frequently, and this was supported by (Reagan, 2018). Many other authors have found in simulator studies and road trials that correctly delivered warnings could improve driver responses in hazardous situations, for example (Abe & Richardson, 2006) (Baldwin & Lewis, 2014) (Kallhammer, 2011) (Parasuraman, et al., 1997) (Politis, 2016).

In unpublished research, Abellio Group trialled the operational use of an aftermarket system that comprised of forward collision warning, headway monitoring, speed limit indicator and lane departure warning. Sixty-six buses were equipped with the system in normal service for more than a year. Interim results suggested a reduction in all collisions of 30% and a reduction in injuries of 60%[2].

Additional consultation with the operator suggests that the collision reduction was based on a substantial number of collisions in the ‘control’ group, though the injury reduction was based on a single figure sample in the control group such that there was considerably more uncertainty in the injury figure. It should be noted that this

[2] https://www.businesswire.com/news/home/20181114005196/en/Abellio-London-Achieves-Significant-Reductions-Collisions-Injuries

system used a forward-facing camera only and so did not provide a warning in situations where cyclists were on the inside of a vehicle turning left. There was also only one incident in the case or control groups involving a pedestrian that would have been in the camera view before the collision. Therefore, the sample was not large enough to prove or disprove any effect of the system on pedestrian collisions.

It is clear from this review that VRU detection systems are currently an important area of research. Although limited by the low number of cases, recent on-road bus trials show positive initial outcomes with the installation of an aftermarket collision detection system. The benefits of this system were, however, reported for the prevention of bus collisions with all collision partners, with only a single case reportedly involving a VRU. Further on-road bus trials are therefore clearly required to understand if this benefit is consistent across larger sample sizes and for different systems.

In lieu of a high-quality evidence base that defines the casualty saving benefits of VRU detection systems, the more reliable data from on-road AEB trials should be combined with human factor research studies. This should link the casualty saving benefits that are associated with the automatic activation of the braking system provided by the AEB system (Table 12), with human factors research that defines how likely it is that a driver will react to a warning/information signal. The conclusions that may be taken from the combination of this research, regarding the effectiveness of VRU detection safety measure solutions, is provided in section 4.7.

4.6 Internal obscurations

No research currently exists that defines the effect that internal obscurations have on VRU casualties. Anecdotal evidence suggests that the effectiveness of driver direct vision may be reduced by driver assault screen (DAS) frame obstructions, poor DAS transmittance and internal reflections. Further research is therefore provided in Section 6.3 to quantify this impact on effectiveness.

4.7 Human factors considerations

The implementation of direct vision, indirect vision and VRU detection safety measure solutions to improve the driver’s ability to detect the presence of other road users in close-proximity to the bus provides clear potential benefits. However, the installation of supplementary devices has the potential to cause an increase in driver workload. The evidence for how driver workload is affected by these particular safety measures has, however, not previously been researched before within the specific context of the DIV safety measure. To understand the effects of shifts in driver workload, one would need to investigate if the consequences associated with the introduction of additional viewpoints, different sized images, distorted images and stitched images outweigh the positive impact of the larger fields of view available. The trade-off between the benefits and limitations of these factors determine how effective the solution is in providing the driver with information that is easy to interpret. The following sections therefore provide a background to driver workload and discuss the derivation of effectiveness estimates based on relevant human factors research.

4.7.1 Driver workload

It is reasonable to assume that for bus drivers who drive the same route (or few routes) every day, they eventually become very well versed in the demands of driving those particular routes. As they become used to the task, they gradually become more skilled at the activity and so can devote less mental resource to maintaining the same level of performance. Highly repetitive processes were noted by Göbel *et al*. (1998) to only cause individuals (the drivers) to show signs of strain in situations where there is a bottleneck of performance (where the situations calls for more of the driver's resource then they can call upon at one time). In a performance bottleneck situation, the driver may have the skills to do all the tasks required, but not concurrently. For example, the driver can check for VRUs in their rear-view mirrors, drive and talk to a passenger as separate activities or even complete two in tandem, but trying to do all three at once may exceed their capacity (causing reductions in the performance of all three tasks). Repetitive situations may also lead to individuals mentally disengaging with the task, leading to slips (performing an unintentional action), lapses (steps in a process missed or goal forgotten in a series of actions) and mistakes (the incorrect course of action to achieve a goal is selected).

The DIV safety measure considers the implementation of several solutions that involve a significant change from the traditional mirrors used by buses and so it is reasonable to expect that these solutions will impact driver workload. These include the use of supplementary mirrors and CMS, CMS replacements for mirrors and VRU detection systems, all of which introduce tasks that are secondary to the primary driving task.

The introduction of secondary tasks has been demonstrated by Lansdown *et al*. (2004) to reduce primary task performance levels, regardless of whether the individual finds the primary task easy or difficult (though performance reduction is much larger when the primary task is difficult). If a driver is also interacting with other systems within the vehicle (e.g. lane monitoring, route guidance, etc.) simultaneously then this may result in significantly more workload than a single secondary task (Lansdown, et al., 2004). Importantly, this increase in workload may also be further exacerbated based on the performance of each particular safety measure solution in relation to the interpretation of the information provided to drivers. Safety measure solutions should therefore aim to optimise the driver interface, whilst the Bus Safety Standard should only require solutions where changes in driver workload do not detrimentally affect outcomes.

4.7.2 Viewpoint locations

The introduction of solutions that require drivers to look at new or additional viewpoint locations and images may increase driver workload. If drivers have to look for critical information in a location where it was not previously located, this will require a period of acclimatisation where drivers become accustomed to new viewpoint locations. As drivers currently only have to look at two viewpoint locations to interpret the information from the indirect vision devices, the addition of new viewpoint locations (through either supplementary mirrors or CMS) will subsequently increase the workload of the driver. In this case, drivers will be required to turn their heads and eyes toward a greater number of points during a potentially hazardous situation, thus reducing the available time for drivers to interpret the images and avoid the realisation of the hazard.

The clustering of images together into the same monitor or mirror cluster may be used to reduce the number of viewpoint locations a driver needs to look towards. Although CMS are much more flexible with respect to clustering, with many current products providing this approach for all fields of vision, a number of clustered mirror devices are also available in the market (see Section 3.3). Mirror clusters are, however, focussed on providing visibility of the fields of vision on each side of the vehicle, meaning that Class I and VI fields of vision would require dedicated mirrors. This would perhaps preclude the future use of mirrors for providing visibility of these field of vision zones, due to the significant increase in driver workload that would be expected.

Clustering of CMS or mirrors images, whichever approach may be adopted, should therefore be encouraged to reduce the number of viewpoint locations a driver is required to look at during manoeuvres. So as not to increase driver workload beyond that which is currently required for current Class II mirror systems, it is recommended that the maximum number of CMS/mirror viewpoint locations that a driver is required to look toward should be two.

4.7.3 Image stitching and tiling

When considering the clustering of mirrors or CMS images there are two approaches that may be adopted for presenting the various fields of view; image stitching and tiling. CMS are capable of stitching images together by fusing signals from multiple camera feeds to present a single image to drivers, whilst mirrors use a single reflective surface that has been bent in continuous sections to different radii of curvature provided. The benefit of image stitching is that a much greater field vision can be provide to the driver within a single image, thus providing a way to reduce the number of stimuli (images) a driver has to interact with in any given situation. To achieve image stitching, however, the image, or at least part of the image, typically requires an element of image distortion, which can also increase driver workload (further information provided in Section 4.7.5).

Image stitching has been taken as far as a CMS that provides a 360° bird's eye view of the area directly surrounding the vehicle. Whilst this provides an enhanced field of vision to the driver, issues exist with image stitching at the boundaries of the field of view of each camera including excessive image distortion and the splitting of images. This all increases the workload of the driver in interpreting the image that is provided to them. (Martin, et al., 2017) estimated 360° CMS systems to have an effectiveness of between 16.7-34.0%, based on an estimated increase in driver workload associated with such a system.

An alternative method is the tiling of images, where a single monitor or mirror housing unit would simultaneously display multiple images. For CMS this would be performed by concurrently providing live video feeds on the same monitor, whilst mirrors would use multiple reflective surfaces that can be adjusted to view different field of vision zones. Although this reduces the number of viewpoints a driver would have to look toward, it increases the amount of time drivers require to process the visual information. This is typically due to the challenges of interpreting information from multiple images that may be showing interacting fields of vision and from smaller image sizes (further information provided on image size in Section 4.7.4).

4.7.4 Image size

Image size can have a significant effect on the ability of the driver to correctly interpret the images, with screen sizes that are both too small and too large resulting in increased driver workloads. Klinke *et al*. (2014) reported that, in an office environment, individuals perceive the workload to be higher during the use of a small screen to conduct visual tasks, when compared with medium or large screens, leading to lower user satisfaction ratings. Klinke *et al*. (2014) found that smaller screen sizes resulted in a 31% increase in the perceived mental demand of participants, when compared to medium and large screen sizes (Figure 16).

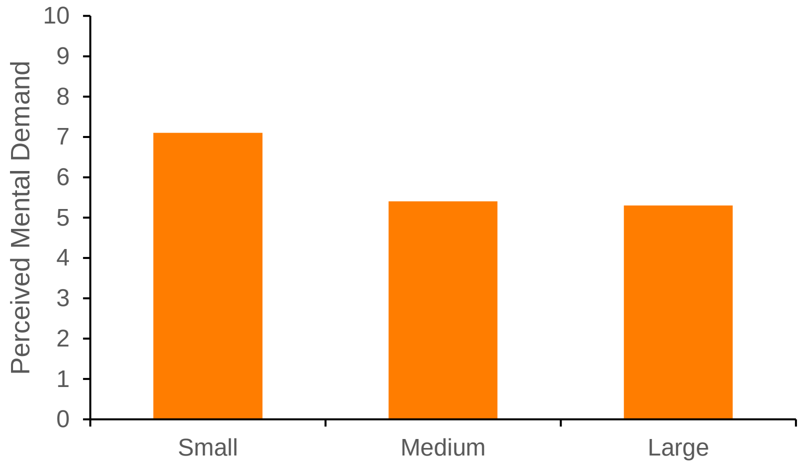


Figure 16: Effects of display size on perceived mental demand. Reproduced from (Klinke, et al., 2014)

When considering the solutions proposed for implementation as part of the DIV safety measure, these changes in perceived mental demand may be used to estimate the potential changes in effectiveness associated with each safety measure solution. The addition of any supplementary field of visions to a single mirror or CMS cluster (Class I/IV/V/IV fields of vision) will result in smaller image sizes, which would result in a 31% increase in driver workload and reduce the overall effectiveness of the safety measure solution by a similar amount. Increasing image sizes will increase the effectiveness of the solution through a 23% decrease in driver workload. As this is relevant to the Class II CMS replacement safety measure solution, which only increases the nearside Class II image size, only the improvement in workload associated with use of the nearside mirror would be realised. In the absence of further detailed information about the relationship between driver workload and effectiveness and the relative uses of the nearside and offside mirrors, improving the image size could potentially lead to an 11.5% improvement in overall effectiveness.

4.7.5 Image distortion

Higashiyama and Shimono (2004) investigated how the curvature of mirror surfaces impact the viewer's perception of the image. This investigation evaluated participant perceptions of target size and distance from mirror for different target sizes, mirror curvatures and distances to target. Through two experiments, this research found that participants perceived the targets to be closer the more planar the reflective surface of the mirror was. Whilst higher levels of curvature resulted in the participants estimating distances to the targets that were similar to the actual distance, planar mirrors resulted in participants estimating target distances to be up to 27% nearer than the real distance.

These conclusions were supported by work performed by Tait & Southall (1998), who state that a decrease in the radius of curvature of a convex mirror corresponds to an increase in the overestimation of the distance to an object by drivers. Tait & Southall (1998) suggest this would result in higher levels of driver workload due to the increased proximal ratios (the size of the object of interest in relation to other things the individual can see in the image) observed in mirrors with greater curvature.

As planar mirrors both improve the proximal ratios observed in the image and lead to an underestimation of the distance to a hazard, it is clear that increasing the distortion of an image (either through greater mirror curvatures or the use of camera lenses that distort images) results in increased collision risks when compared to the planar mirrors currently installed across most of the TfL fleet. In the absence of relevant on-road trial data, it is therefore suggested that any DIV safety measure solutions intending to provide drivers with distorted images reduce the effectiveness of their solution by 27%, based on the outcomes of the research by Higashiyama and Shimono (2004).

4.7.6 Human-machine interface of VRU detection systems

The human-machine interface (HMI) of the VRU detection safety measure solutions assessed in this report is also a key element by which the potential effectiveness of the solution should be evaluated. It is globally recognised that a poorly designed HMI will limit the technical benefits of VRU detection solutions, whilst a well-designed HMI is critical to maximising these benefits.

When considering the purpose of a VRU detection system (see Section 4.5), it is clear that such a system may provide a range of signals and interventions based on the urgency and criticality (i.e. priority) of a situation. Mid-level priority information signals may be provided to drivers in situations where VRUs are in close-proximity to the bus, but where a collision is considered to not be imminent. High-priority warning signals, however, should be provided to drivers when a collision with a VRU is imminent (i.e. a time to collision of <2 seconds). Finally, interventions, such as braking/motion inhibit systems, could also be used to prevent, or mitigate the effects of, collisions with VRUs should the driver not appropriately respond to the warning signal. These may also be used in tandem through escalating the priority level of the VRU detection system in response to changes in the urgency of an emerging/critical situation.

ISO 15006 and ISO 15008 provide guidance on the design of an effective HMI for the provision of information and warning signals (see Section 5), and are based on the general guidelines for effective warning/information signal HMI design established by the UNECE Informal Working Group on Intelligent Transport Systems (UNECE, 2011). These internationally agreed guidelines establish eight key principles for the design of high-priority warning signals:

1) High-priority warnings should be noticeable in the driving environment
2) High-priority warnings should be distinguishable from other messages
3) High-priority warnings should provide spatial cues to the hazard location
4) High-priority warnings should inform the driver of proximity of the hazard
5) High-priority warnings should elicit timely responses or decisions
6) Multiple warnings should be prioritized
7) False / nuisance warning rate should be low
8) System status and degraded performance of high-priority warnings should be displayed

The first four principles relate to driver detection and identification of hazards, numbers 5 and 6 correspond to the decision and response of the driver, while numbers 7 and 8 concern the driver's awareness of system state, trust and reliability. To ensure that the HMI of VRU detection solutions is effective, it is therefore recommended that future Bus Safety Standard requirements adopt these principles to assess the performance of VRU detection systems.

As previously discussed in Section 4.5, the casualty saving benefits of highly effective VRU detection systems has never previously been quantified. Effectiveness estimates for the detection of a VRU have, however, been quantified by Rosen (2013) for AEB systems, which would typically use a similar approach for the detection of VRUs. However, Rosen (2013) does not quantify the effectiveness of the driver's response to a warning signal. Human factors research by Kuehn *et al*. (2009) does establish a human-machine interface factor of 80%, which estimates the response rate of the driver to positive detections of VRU hazards. It is recommended, therefore, that this driver response correction factor is applied to the effectiveness estimates abstracted from Rosen (2013), to estimate the overall effectiveness of VRU detection systems.

4.8 Summary of solution performance evidence

The previous sections provide a review of the literature to determine the evidence base underpinning the effectiveness of a range of proposed safety measure solutions for the four secondary safety measures: Direct Vision (DIR), Indirect Vision (IND), VRU Detection (DET) and Internal Obscuration (IOB). This state-of-the-art review found that high-quality relevant research had only been performed for the DIR safety measures. Each subsection reviews the range of research performed for each safety measure, with all subsections highlighting a current paucity in high-quality and relevant research relating to each proposed solution. Several subsections, therefore, conclude that more relevant research is required to improve the evidence base that underpins the overall effectiveness values to be used for the proposed safety measure solutions.

Section 6 considers the generation of an evidence base that underpins the overall effectiveness values used for each safety measure solution to direct future efforts towards the most effective solutions. This may be coupled with Section 5, which highlights the current regulations, standards and test procedures that are relevant to the four DIV safety measures, to understand what existing testing protocols may be used as a precedent for future Bus Safety Standard testing and assessment protocols.

5 Existing standards and test procedures

5.1 Introduction

This section includes reviews of protocols, regulations and standards relevant to the Improved Direct and Indirect Vision (DIV) safety measure. The regulations and standards identified to be relevant to this safety measure are:

- UN Regulation Number 107 (M2 and M3 vehicles);
- UN Regulation Number 46 (Devices for Indirect Vision);
- UN Regulation Number 43 (Safety Glazing);
- BS ISO 16121-2:2011 (Visibility);
- BS ISO 16121-3:2005 (Information devices and controls);
- BS ISO 15006:2011 (In-vehicle auditory presentation);
- TfL HGV Direct Vision Standard (DVS) star rating scheme;
- TfL Test and Assessment Procedure for HGV Blind-spot Safety Devices;
- Proposal for a UNECE Regulation on Blind Spot Information Systems; and
- TfL Vehicle Operational Refurbishment Specification.

Each of the listed documents has been reviewed in the sections below.

5.1.1 UN Regulation Number 107 (M_2 or M_3 vehicles)

5.1.1.1 Summary of regulation

UN Regulation Number 107: Uniform provisions concerning the approval of category M_2 or M_3 vehicles with regard to their general construction (UN R107) applies to the majority of single-deck, double-deck, rigid or articulated vehicles of category M_2 or M_3 (UN, 2016). The regulation lays out requirements for various aspects of bus design including floor space, wheel chair access and staircase design. UN R107 does not include vehicles specially designed for the movement of school children.

Vehicles which have a capacity exceeding 22 passengers (in addition to the driver) can be split in to three classes:

- Class I vehicles are constructed with areas for standing passengers, to allow frequent passenger movement (e.g. city buses);
- Class II vehicles are primarily constructed for seated passengers but allow the carriage of standing passengers in the gangway and/or in an area which does not exceed the equivalent space of two double seats; and
- Class III vehicles are constructed exclusively for seated passengers. If a vehicle fits in to two categories it must be approved for each one.

M_2 or M_3 vehicles with a passenger capacity not exceeding 22 can be broken down in to either:

- Class A (vehicles designed to carry standing passengers; a vehicle of this class has seats and shall have provision for standing passengers); or
- Class B (vehicles not designed to carry standing passengers; a vehicle of this class has no provision for standing passengers).

5.1.1.2 Relevance to M_3 category vehicles and project

UN R107 defines categories of bus and lays out requirements for various aspects of bus design. Key points taken from the regulation related to vision include visible areas inside and outside non-automated service doors and how to achieve them.

If the direct view from the driver's seat is not adequate, due to internal obstructions, optical or other devices can be installed to allow the driver to detect the presence of a passenger in the immediate interior or exterior of every side service door which is not an automatically-operated service door (a service door is a door intended for use by passengers in normal day operations with the driver seated). In the case of Class I double-deck vehicles, this requirement also applies to the immediate vicinity of each intercommunication staircase on the upper deck.

If the service door is in the rear of the vehicle (not exceeding 22 passengers), the driver must be able to detect the presence of a person 1.3 m tall standing 1 m behind the vehicle.

Driving mirrors, defined in UN Regulation Number 46: Uniform provisions concerning the approval of devices for indirect vision and of motor vehicles with regard to the installation of these devices (see following section), may be used to meet the requirements described above provided that the field of view required for driving is still met (UN, 2016). This does not apply to doors situated behind the articulated section of an articulated vehicle.

5.1.2 UN Regulation Number 46 (Devices for Indirect Vision)

5.1.2.1 Summary of regulation and tests

The purpose of UN Regulation Number 46: Uniform provisions concerning the approval of devices for indirect vision and of motor vehicles with regard to the installation of these devices (UN R46) is to define a minimum visible ground plane a driver must be able to see through the use of indirect vision devices e.g. mirrors or Camera Monitoring Systems (CMS) (UN, 2016).

UN R46 sets out seven main vision requirements (Class I - VII) and installation criteria for M, N and L1 (with bodywork at least partly enclosing the driver) category vehicles (see Figure 4). Out of these seven ground planes, Class II (Main rear-view) is the only compulsory vision zone for M_3 category vehicles.

Ground planes

Class II ground planes are a mandatory requirement on both the offside (driver) and nearside (passenger) of the vehicle. The class II ground planes are shown by the dark grey areas in Figure 4. Both the offside and nearside areas are measured using the same points and dimensions.

Class I (Rear-view (interior)), IV (Wide-angle view), V (Close-proximity view) and VI (Front-view) are optional for M_3 category vehicles (see Figure 4). Class I has no defined requirements for field of vision so is not shown in the diagram and will not be reviewed in detail.

The Class IV ground planes are shown in light orange in Figure 4 and are measured from a point on the outermost edge of the vehicle and 1.5 m rearwards of the driver's ocular points. The ground plane can be provided on the offside and or the nearside of the vehicle.

If used on an M_3 vehicle, the Class V ground plane (shown in dark orange) is required to be visible on both the offside and nearside, unlike for N_2/N_3 vehicles. The nearside ground plane is larger than that defined for the offside. A 2 m radius may be permitted to the front nearside corner. The larger ground plane requirements shown in mid-grey in Figure 4 (for the N/S) do not apply when any part of a class V mirror (including the holder) is positioned less than 2.4m above the road surface.

For HGVs, if the class V ground plane is visible through a combination of the views provide by the Class IV and VI devices, a class V device is not compulsory.

The Class VI ground plane is optional for category M_3 vehicles and provides a visible area for the driver that extends 2m from the front of the vehicle and 2m from the outer most point of the near side of the cab. A 2m radius may be permitted to front nearside corner. If this ground plane cannot be seen using a mirror, a vision support system can be used instead. This system must be able to detect an object 0.5 m high with a diameter of 0.3 m within the Class VI ground plane.

In the case of HGVs, the Class VI ground plane is not mandatory if the driver is able to see a straight line 0.3m in front of the vehicle and at a height of 1.2m above the road surface. The line extends between two vertical planes that are parallel to the longitudinal vertical median plane and are positioned at the outermost offside edge of the vehicle and a point 0.9m outboard (outside) of the outermost nearside edge of the vehicle.

Camera monitoring systems

UN R46 also sets out how Camera Monitoring Systems (CMS) may be used instead of a mirror to view a specific ground plane. If a CMS is fitted, the field of vision must be at least the same as the equivalent mirror and meet the minimum requirements set out in this regulation.

A CMS must provide a clear and smooth image in a variety of environmental conditions such as sunlight shining directly in to the lens. Tests to assess this performance are included. For example, a test is defined to assess the proportion of screen in which the luminance contrast ratio of a high contrast pattern falls below a predefined level.

There is no requirement for a minimum number of cameras on a bus, so long as the image presented to the driver is at least the equivalent quality as the mirror it is replacing. There is however a limit to how many CMS monitors can be installed in the cab. To prevent driver sensory overload, the number of monitors cannot exceed the number of mirrors required to view the ground plane e.g. a CMS designed to replace Class II bus mirrors can have up to two monitors, one each side.

Dual purpose monitors may be installed in the cab as part of a CMS. If a dual-purpose screen is used, the monitor must display the relevant fields of vision to the driver when the ignition or the vehicle master control switch is in the on position (dependant on vehicle) until the vehicle reaches a speed of 10 km/h, forwards or backwards. After this speed has been attained, the monitor (or section of monitor) displaying the Class VI ground plane may be used for other functions such as navigation or other Infotainment features. To avoid confusing the driver, non-continuous images (i.e. different fields of view within the same monitor) need to be clearly separated from each other. A combined continuous image, e.g. 360 bird's eye view, without clear separation is allowed.

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

Any external CMS component that has been installed in the recommended manufacturer position, irrespective of any driver adjustment shall be assessed using a 100 mm diameter sphere. Any features which could be in contact with the 100 mm diameter sphere when it is placed against the component must have a minimum radius of curvature of 2.5 mm. The diameter of the sphere is increased to 165 mm for any internal parts e.g. CMS monitor. Any edges of fixing holes or recesses which have a diameter or where its longest diagonal is less than 12 mm are exempt from the radius requirements mentioned above if they are blunted. In addition to this, if any camera or monitor components have a Shore A hardness of less than 60 and are mounted on a rigid support, the requirements shall only apply to the support.

Installation

A device for indirect vision shall be positioned in such a way that the driver has a clear view to the front, rear and sides of the bus while sitting in their normal driving position with minimal obstruction. The centre of a monitor should not be below a plane passing through the driver's ocular points and declined 30° below. It should also be roughly in the same direction as the mirror it is replacing e.g. A-pillar mounted Class II screen.

If the lower edge of a Class II to VII (excluding Class V and VI) mirror is less than 2 m above the road surface, 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). Class V and VI mirrors cannot be installed lower than 2 m above the ground (including post adjustment position) 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 offside Class II mirror must be able to be adjusted from inside the cab while the door is closed. The window may be open to complete this task.

In the case of Classes II, IV, V, and VI ground planes, 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 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 vertical monitoring screen.

Testing

To reduce the risk of injury to VRUs in close-proximity to the vehicle or damaging the component, a device must not protrude any further, from the sides of the vehicle, than necessary to achieve the vision requirements for its relevant class. Indirect vision devices are required to have two impact tests. The tests are conducted using a pendulum and requires the reflecting surface not to break during the test. unless one of the following conditions is met:

- Any fragments remain glued to the back of the housing (partial separation of 2.5 mm either side of the crack is acceptable). Small splinters are permitted at the point of impact.
- 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.

An impact test is not required when:

- 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);
- 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.

5.1.2.2 Mirrors for buses with enhanced front end designs

UN R46 sets out the minimum visible ground plane a driver must be able to see from their vehicle using assistive devices e.g. mirrors or Camera Monitoring Systems (CMS) (UN, 2016) The ground planes relevant to category M_3 vehicles (Class II (mandatory), Class IV, V and VI (Optional)) have been developed with the current vehicle designs in mind, primarily flat fronted vehicles. However, the designs for future vehicles could include a range of cab profiles and therefore, consideration of these potential designs with the existing defined ground planes is provided below.

A driver sat forward and in a central driving position using vision requirements complying with UN R46 may experience blind spots to the rear because of the Class II and IV ground planes being incompatible with certain rounded cab profiles. Therefore, the defined ground planes may have to be updated to account for potential new blind spots.

The installation of mirrors to view these additional blind spots may also be impractical. Indirect vision devices must not protrude any further from the sides of vehicle than necessary to fulfil the vision requirement. Furthermore, mirrors mounted below a certain height have a protrusion limit; if either of these scenarios occur an equivalent CMS could be used instead.

Certain designs may allow a cross over in Class IV and VI field of vision (optional fitment), eliminating the need for a Class V device.

UN R46 allows bodywork to obstruct up to 10% of the Class VI field of vision. This may be particularly relevant where the design of the front end has been modified.

5.1.2.3 Relevance to M_3 category vehicles and project

UN R46 is relevant to M_3 category vehicles and this project because it outlines the minimum visible ground plane a bus driver must be able to see through indirect vision devices; specifying how these ground planes can be made visible through correct installation and possible device combinations. The regulation sets out how CMS can reduce, or replace entirely, the number of mirrors without causing additional sensory overload or blocking the driver's field of vision. As well as assisting the driver, UN R46 also considers VRUs in close-proximity to the vehicle and occupants by defining a minimum impact performance for external and internal components.

The Class II ground plane is the only compulsory vision zone for M_3 category vehicles. Class IV, V and VI ground planes are optional for buses but compulsory for HGVs. This is partially because HGV cabs are significantly higher than buses. This is especially the case for N3g category vehicles (off-road variants in excess of 12 tonnes) where a recent study (Summerskill, et al., 2015) found N3g vehicles are on average 32% taller than their distribution variant. Low Entry Cab HGVs e.g. Dennis Eagle Elite 6 are more comparable to bus designs but are still required to be fitted with equipment to provide a view of all four defined ground planes.

However, as previously described, there are exceptions to fitting certain classes of indirect vision devices. UN R46 states that if the driver of a HGV 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 (UN, 2016) In addition to this a Class V indirect vision device is not required if there is sufficient cross over in driver field of vision afforded by the Class IV and VI mirrors. The mirror and CMS impact testing procedure outlined in UN R46 (UN, 2016)could be modified to test folding mirror clusters. Impact force values could be used as a maximum force to move the cluster.

5.1.2.4 Comparison with other approaches: BS ISO 16121-2:2011

BS ISO 16121-2:2011 Road vehicles — Ergonomic requirements for the driver's workplace in line-service buses Part 2: Visibility (BS ISO 16121-2) sets out minimum vision requirements for line-service buses (BSI, 2011a). To reduce the size of the forward blind spot, at least 95% of a bar (equal in length to the width of the vehicle), placed in front of the bus at a height of 1100 mm above the ground and 300 mm from the foremost surface (see point 4 in Figure 17), should be directly or indirectly visible from both vision point V_1 and V_2. Vision point V_1 and V_2 are located 635 mm vertically above the H-point when the seat in its rearmost highest and in its foremost lowest position, within the required seat H-point adjustment range specified in ISO 16121-1 (labelled 2 in Figure 17) (BSI, 2012).

If this requirement cannot be met by direct vision alone, an indirect vision device (e.g. CMS or additional mirror) must be provided to supplement the driver's field of vision (labelled 3 in Figure 17). Any obstruction caused by the steering wheel shall not be taken in to consideration.

If there is a service door (door intended for use by passengers) located at the front corner of the vehicle (labelled 1 in Figure 17), a 100 mm x 100 mm x 100 mm cube (labelled 5 in Figure 17, centre) positioned externally adjacent to the, foremost window in the door and 800 mm above the ground must be directly or indirectly visible to the driver. The cube is considered as visible if a minimum of ¾ of one face of the cube can be seen from points V_1 and V_2.

If the vehicle is equipped with an adjustable dashboard, the measuring points for the forward and lateral blind spot tests must be taken when the dashboard is in its mid position, as defined by the manufacturer.

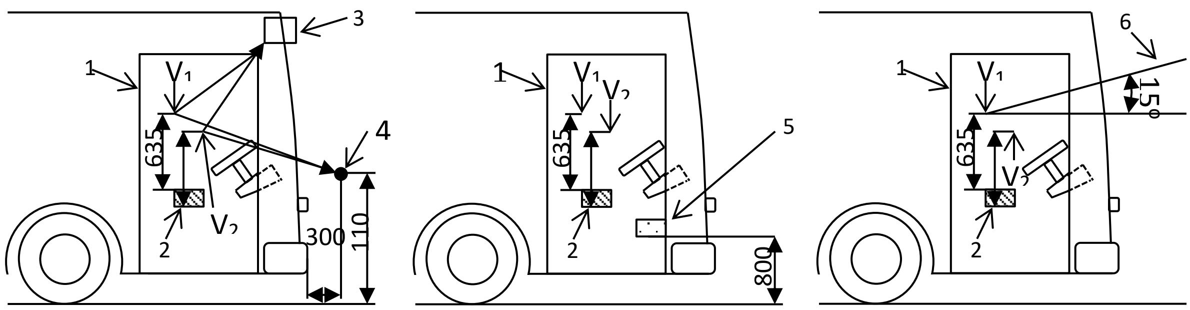


Figure 17: Method for testing the forward (left) and lateral (centre) blind spots and upper forward (right) vision of line-service bus, diagram adapted from (BSI, 2011a)

To maintain a sufficient view of traffic lights and other overhead roadside infrastructure, the design must enable the driver to have an unobstructed view through the windscreen measured between a horizontal plane intersecting with V_1 a plane inclined at 15° (labelled 6 in Figure 17, right). Any obstruction caused by rear view mirrors, windscreen wiper arms; video screens, sun visor or any legally required component is ignored during the assessment.

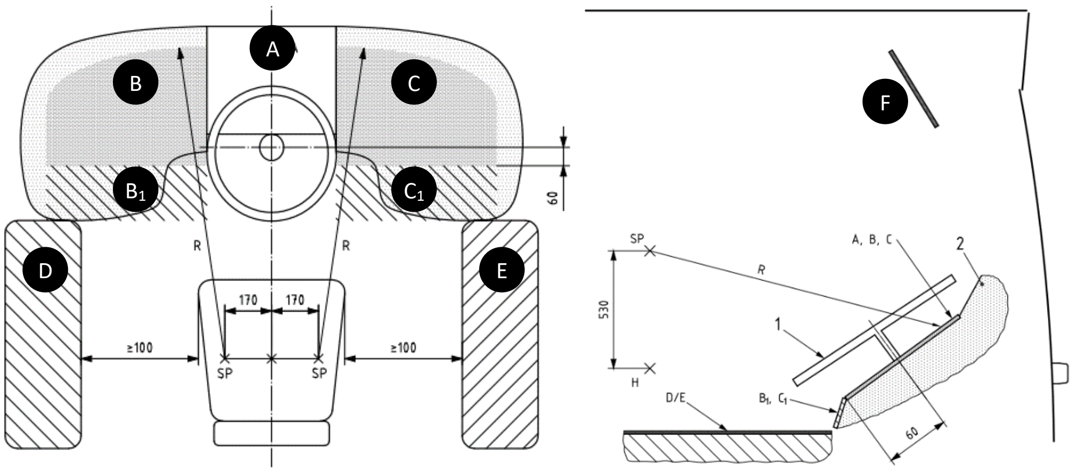
Mirrors and/or other indirect vision devices must be provided to enable the driver to observe key passenger compartment areas, specifically gangways, exit and entrance zones, which are outside of the driver's direct field of vision.

The design should avoid obstructing the view outside of the vehicle and of vehicle controls and information devices and controls by reducing reflections caused by light sources (or other illuminated objects) and reflections from sunlight. Reflections in the windscreen created by interior light sources should also be minimised as these could interfere with the driver's judgement.

BS ISO 16121-2 develops upon various aspects of UNR46: (UN, 2016) . The forward blind spot test is somewhat comparable to the Reg 46 Class VI ground plane exemption and ensures the driver can see VRUs directly in front of the vehicle. The lateral blind spot vision requirements cover a similar area to the Class V ground plane, this will allow the driver to better detect VRUs travelling parallel to the front nearside of the bus during safety critical manoeuvres e.g. left turn. According to UN R46, a Class I (Rear-view) interior mirror is not mandatory and has no set field of view (UN, 2016). In BS ISO 16121-2 indirect vision devices are required to view key internal passenger compartment areas not visible by direct vision (BSI, 2011a). These devices may not require checking during turning manoeuvres but could be considered a form of distraction when the vehicle is stopping at or pulling away from a bus stop.

5.1.2.5 Comparison with other approaches: BS ISO 16121-3:2005

BS ISO 16121-3:2005 Road vehicles — Ergonomic requirements for the driver's workplace in line-service buses Part 3: Information devices and controls (BS ISO 16121-3) lays out approximate locations for key information devices and controls within the bus cab (specifically the instrument panel). It ensures fundamental ergonomic principles, relevant to instrument panel design e.g. red lamp or screen colour for warning, are followed during the design process (BSI, 2011b). The standard splits the bus cab into six main zones (A-F) based on frequency of use and distance from the driver (see Figure 18) and details which controls, or displays can be placed in particular zones.



Small person hand reach range (R): 750 mm from shoulder point (SP)

Figure 18: Definitions of zones, plan view (left) and side view (right)

In relation to the direct and indirect vision sub-measure, Zones A and B are the most relevant regarding CMS monitor location. Zone A covers the dashboard area beneath the steering wheel and is defined by a horizontal tangent to the top of the steering column, a vertical line projected from the left- and right-hand extremities of the wheel rim and the top of the dashboard. The central information display and the warning and alert indicators are located within this region.

Zone B covers the area to the left of the steering wheel. This zone is limited to the right by the outer diameter of steering wheel, to the left and front by the hand reach envelope (see dimension R in Figure 18) and from the lateral plane up to a maximum of 60mm rearwards from the steering wheel centre. Amongst light controls, it is also an alternative location for a video monitor. The positioning of video monitors is not limited to within the hand reach limit.

Zone C (Figure 18) uses the same measurements as Zone B but is mirrored to the right-hand side of the steering wheel. This zone is occupied by the door control switch, bus stop brake and a selection of other controls. It could be an ideal location for a CMS monitor, displaying a video feed of the offside of the vehicle, as it is close to the looking ahead position and many of the controls in Zone B have the option of being installed in Zone E depending on the design of the cab (on right hand drive vehicles).

Zone F (Figure 18) covers the roof console over the driver's workplace. It is out of the hand reach of a seated driver and is intended for controls for equipment not frequently operated such as video monitors. This area could be developed in future designs to include CMS feeds or Head-up Displays (HUDs) as it is in line with the height of the side mirrors and keeps the driver looking up and ahead.

The standard recommends that zones A to F can be inclined towards the driver at an angle between 10° and 20° for the best ergonomic operation.

BS ISO 16121-3 differs to UN R46, with regards to CMS monitor location, by defining specific zones for key displays or controls as opposed to areas where the driver is used to looking (e.g. mounted on A-pillar to replace a mirror) (BSI, 2011b; UN, 2016). If manufacturers start replacing mirrors with CMS, ISO 16121 may need to be updated to ensure monitors can be placed in positions that allow them to remain compliant with UN R46 (e.g. Zone C for offside CMS monitor).

5.1.3 UN Regulation Number 43 (Safety Glazing)

UN Regulation 43: Uniform provisions concerning the approval of safety glazing materials and their installation on vehicles (UN R43) defines the minimum safety and performance requirements, e.g. minimum safety glazing, for all windscreen and other safety glazing (UN, 2017). In context to this piece of legislation "other safety glazing" is defined as all glazing situated in front of a plane passing through the driver's R-point (seating reference point) and perpendicular to the longitudinal median plane of the vehicle through which the driver can view the road when driving or manoeuvring the vehicle e.g. the Driver Assault Screen. To ensure the driver has a clear forward field of vision whilst looking through the DAS, UN R43 states the regular light transmittance for a windscreen and safety glazing (other than windscreens), required for the driver's forward field of vision shall be no less than 70%.

5.1.3.1 Relevance to M3 category vehicles and project

UN R43 sets out the minimum safety and performance requirements for all safety glazing fitted to a vehicle (UN, 2017). The transmittance requirements are particularly important for M_3 vehicles as they ensure the driver has a clear forward field of vision that is free of any obstructions such as tinting. This helps with detecting VRUs travelling in close proximity to the vehicle, e.g. undertaking cyclist, or those approaching safety critical zones, e.g. pedestrian crossing from front nearside corner.

5.1.4 ISO Standards for Ergonomic Aspects of Information and Control Systems

5.1.4.1 BS ISO 15006:2011 (In-vehicle auditory presentation)

BS ISO 15006:2011 Road vehicles — Ergonomic aspects of transport information and control systems — Specifications for in-vehicle auditory presentation (ISO 15006:2011) outlines the minimum safety and performance criteria for audible notifications or warnings within a vehicle (BSI, 2011C)). The standard breaks audible notifications or warnings in to two main categories, speech and tonal (non-speech).

The recommended frequency range for in-vehicle auditory signals is between 200 Hz and 8000 Hz. The main component of a tonal signal should be between 400 Hz-2000 Hz to allow for drivers with age-related hearing loss. A broadband signal or a mix of narrowband signals with distinctly separated centre frequencies should be used to aid detection and direction. The character of the signal should reflect its urgency and should be as loud as suitable (a noise that is too loud or sudden could lead to unsafe driving due to defensive reactions or startle reflexes). The signal-to-ambient ratio of a tonal signal must be greater than 1:3 and be at least 10 dB above the masked threshold of the ambient noise.

ISO 15006:2011 sets out three time categories based on the urgency of the message. These are as follows:

- Short-term response: 0 s – 3 s;
- Medium-term response: 3 s – 10 s; and
- Longer-term response: > 10 s.

Different sound levels and patterns should be used to differentiate between the criticality levels and from non-safety signals.

Time-critical auditory safety warnings always have priority over non-safety critical auditory signals, even if the non-safety signals are time-critical. A short-term auditory signal should be sent to the driver immediately after a critical event is detected by the Vehicle's Transport Information and Control Systems (TICS). The sound itself should take less than approximately 30 ms to reach full loudness. A medium-term response auditory signal may be sent with a time delay of up to 10 s depending on competing signals. Auditory signals within the long-term category may be delayed so long as the driver still has sufficient time to plan and execute an appropriate response to the signal.

Tonal signals (non-speech) have two primary functions; attracting driver attention and providing specific information. The number of tonal signals used in a vehicle should be limited to reduce driver workload. If a tonal signal alongside a visual warning, both must be displayed at the same time. An intermittent or continuous (until an appropriate action is taken by driver) tonal signal should only be used in special circumstances e.g. very important messages affecting the safety of the vehicle occupants or the capability to drive the vehicle.

Speech coding should only be used if the driver has sufficient time to listen to the full message before having to react. The message should use simple vocabulary which shares consistent language with any written notifications. Messages should be kept short, concise and contain no more than five information units. If further information is required, then the message should be split into separate groups of five. The more urgent the message is, the fewer words and units of information should be used. In the case of complex auditory or speech information, the driver may be helped in the following ways:

- Sequencing the units of information in order of potential relevance:
    - to help the driver to quickly decide whether to “tune-in” or “tune-out”, depending on the auditory signal content
    - placing the action-related unit of information at the end
- Providing key words (e.g. “traffic signal”), prosodic (linguistic) cues and highlighting;
- Providing redundant visual displays, at least for the principal units of information, particularly for long-term auditory signals;
- Providing a means for the driver to request that the auditory signal be repeated; or
- Providing a way to stop the auditory or speech information.

A signal concerning the safety of the driver or other people and requiring immediate action by the driver cannot be communicated via an auditory signal alone. It must be transmitted via another additional sensory channel such as visual, haptic and/or kinesthetic feedback. This redundancy is vital as some drivers may miss it due to hearing impairment or masking ambient auditory noise.

5.1.4.2 BS ISO 15008:2017 (In-vehicle visual presentation)

BS ISO 15008:2017 Road vehicles — Ergonomic aspects of transport information and control systems — Specifications and test procedures for in-vehicle visual presentation (ISO 15008:2017) is primarily focused on ensuring that images and writing on the visual displays are legible to the driver (BSI, 2017). The standard defines two types of display formats; positive and negative. A positive display refers to an interface with dark symbols displayed on a light background. The reverse applies to a negative display.

During daylight conditions either format may be used (some instrument clusters are designed to shade displays) however during night time, or on instrument clusters which shelter the display, a negative display should be used. If a display is not sheltered a positive display can be used to reduce the impact of reflections.

For physiological and psychological reasons, not all symbol/background colour combinations are acceptable within a vehicle. Attention should be given when selecting colours to ensure certain symbol/background colour combinations are avoided.

Flashing Images should be used only to attract attention and inform about critical conditions requiring an immediate action. In order to attract attention, a flash frequency of 1 Hz to 5 Hz with a duty cycle of 50 % to 70 % should be used.

In addition to ISO 15006:2011 & ISO 15008:2017, BS ISO 15007-1:2014 Road vehicles — Measurement of driver visual behaviour with respect to transport information and control systems Part 1: Definitions and parameters and ISO/TS 15007-2:2014 Road vehicles — Measurement of driver visual behaviour with respect to transport information and control systems Part 2: Equipment and procedures were also reviewed however no relevant information could be found (BSI, 2011C; BSI, 2017; BSI, 2014a; BSI, 2014b).

5.1.4.3 ISO/TS 16951:2004 (Technical Specification for Ergonomic Aspects of Information and Control Systems)

ISO/TS 16951:2004 Road vehicles - Ergonomic aspects of transport information and control systems. This standard defines a procedure for determining priority of messages presented to drivers defines four levels of message criticality based on road user injury and vehicle damage (ISO, 2004). The four levels can be seen in Figure 19.

Figure 19: Critically levels and descriptions. Diagram adapted from (ISO, 2004)

The urgency has been defined based on the time within which the driver action or decision has to be taken if the benefit intended by the system is to be derived from the signal (Figure20) (ISO, 2004).

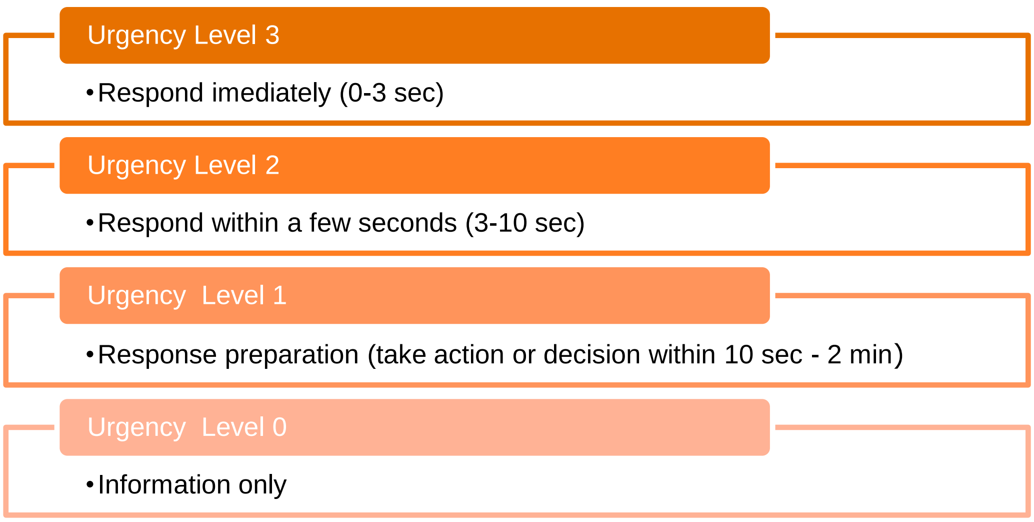


Figure 20: Urgency levels and descriptions. Diagram adapted from (ISO, 2004)

Many collision warning systems are designed to work in situations where severe injury or fatality are possible outcomes. Guidelines on establishing requirements for high-priority warning systems (UNECE warning systems guidelines) (UNECE, 2011) simplifies the above diagrams based mainly on the urgency of the warning. These simplified warning levels are shown in Figure21.

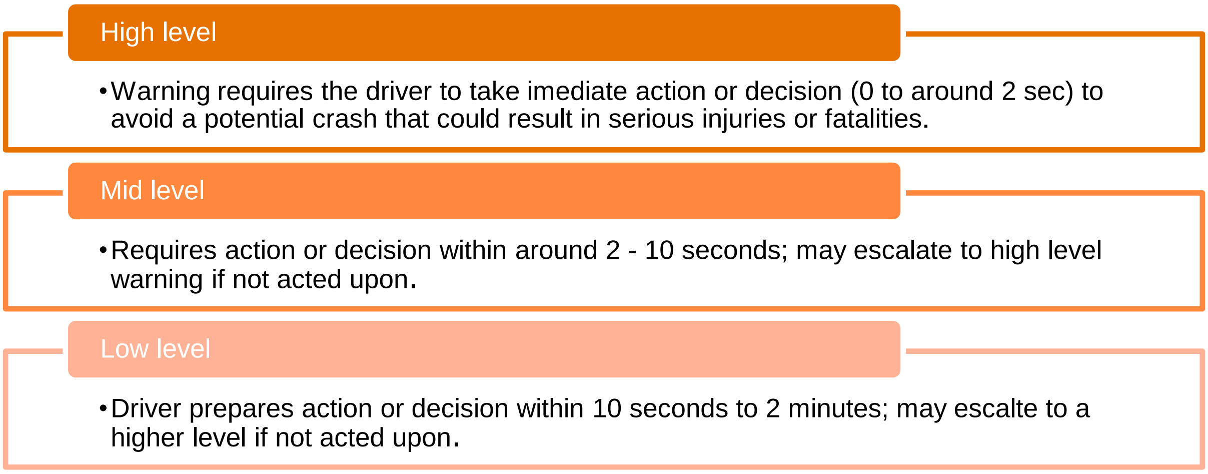


Figure 21: Simplified warning levels

5.1.4.4 Relevance to M_3 category vehicles and project

A range of ISO standards which define the type of warning, application of warning and criticality levels, have been reviewed in the sections above and by Knight, et al. (2017). Low-level situations, as defined in the UNECE warning systems guidelines, are likely to occur on a very frequent basis compared to high level situations which require two seconds to act upon (UNECE, 2011). Therefore, it makes sense for the least alerting and least annoying warning modes to be used for the frequent, low urgency incidents. Thus, audible (tones) and multiple mode warnings should not be used for low urgency events. Conversely, the most urgent events demand the most alerting techniques. Thus, speech should not be used for urgent warnings. The fact that they are rarely issued means that although they are individually more annoying and intrusive, the cumulative level of annoyance during driving over a substantial period will remain low. The warning needs to draw the driver's attention in the direction of the hazard such that they can quickly gain sufficient situational awareness to make the right choice of avoidance action and implement that action quickly. Thus, the test method developed by (Knight, et al., 2017) rewarded systems that had directional warnings and staged approaches of increasing urgency as a collision became more likely. This could have been implemented by early warnings using speech to locate the hazard, or visual warnings adjacent to where the VRU was most likely to be seen, for example a warning lamp adjacent to the A-pillar/nearside mirror for a cyclist at the side of the HGV. This might be combined with later multi-mode warnings when a collision became imminent.

5.1.5 The HGV Direct Vision Standard (DVS) Star Rating Scheme

5.1.5.1 Summary of regulation and tests

The HGV Direct Vision Standard (DVS) was originally proposed as a method of scoring the amount of direct vision provided by various models and configurations of HGVs operating in London by adopting a five-star rating scheme. TfL plans to remove the majority of zero-star rated trucks from London by 2020 and have a three-star minimum safety standard by 2024. In the future, localised minimum standards could restrict low scoring HGVs from entering specific areas which have a high concentration of VRUs.

In 2015, TRL drafted a Direct Vision Standard 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 of the report describing the definition of the Direct Vision Standard (Robinson, et al., 2016)

The assessment of the field of view is conducted on a CAD model that is accurate to within ±2 mm of the real vehicle and its required set up. The height of the cab is determined by several key factors;

- The suspension and tyres must be 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 must be occupied by a driver with a mass of 68 kg;
- There must be no additional payload or ballast added to the vehicle; and
- The centre-point of the HGV steering wheel 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 obstruct the driver's field of vision. If the feature is used on a regular basis (e.g. mirror) the feature must be positioned in it's in-use position. If the feature is not used on a regular basis (e.g. windscreen wipers) then it must be positioned in its stowed position. The passenger seat must be positioned mid-point between the fully forward and backwards position.

Using collision data and anthropometric data, the project defined a minimal visible area for the front and nearside of an HGV. The two zones were then split in to two horizontal layers (creating four sub zones) (see Figure 22). 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).

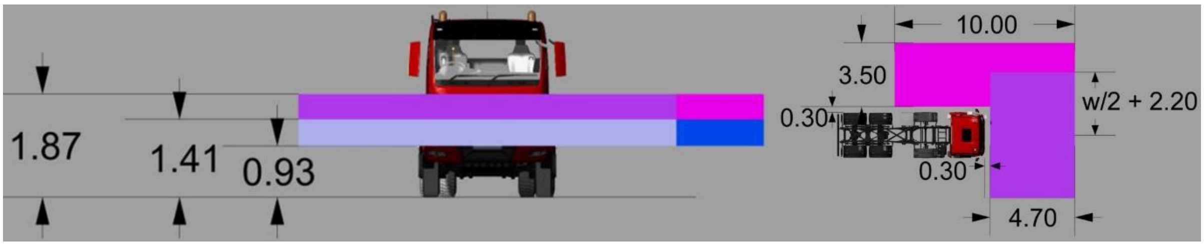


Figure 22: Vision Zone Dimensions (w is width of vehicle) (Robinson, et al., 2016)

A score is calculated by projecting the area visible from the cab, by at least one of two eyes of a 50th percentile UK male driver, into the assessment zones then subtracting the visible volume from the assessment zones. This leaves only the vehicle blind spots (see Figure 23).

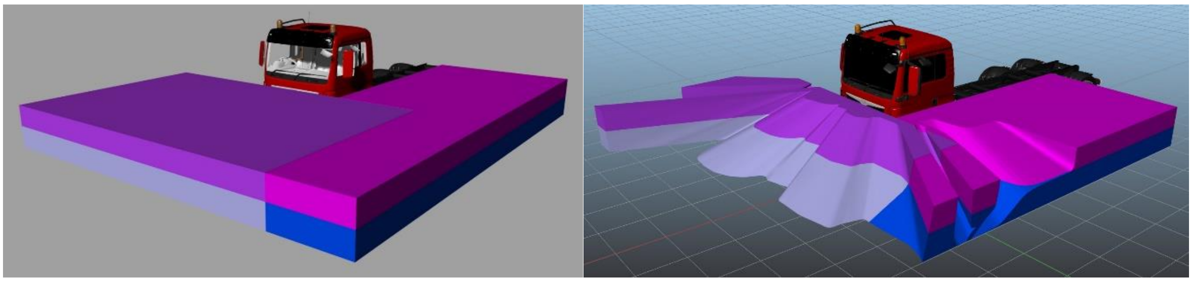


Figure 23: Standard N3G assessment zones before (left) and after (right) the visible volume is subtracted (Robinson, et al., 2016)

The visible volume is then multiplied by a weighting for each of the sub zones shown in Table 13 and added together to produce the overall score.

Table 13: Vision Zone weightings, table adapted by (Robinson, et al., 2016)

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 given their rating using the ranges found in Table 14.

Table 14: DVS rating 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

During the developmental stages of the project, Robinson et al (2016) scored a selection of HGV designs, including a standard N3G and Low Entry Cab, to test the method. The standard N3G scored 0.39, the equivalent of zero stars, and the Low Entry Cab scored 0.65, the equivalent of five stars

At the time of drafting the Bus Vision Standard protocols the Loughborough Design School (LDS) and TfL DVS had yet to be published. Since then it has now become available to view (Summerskill, et al., 2018). A list of key differences between the TRL and LDS protocol are:

Different Vision Zone dimensions (see Figure 24);

- The nearside, front and offside of the vehicle are all assessed
- The 0.3 m offset from side of vehicle has been removed and replaced with an exclusion area running parallel to the front and side vertical surfaces of the vehicle
- There is a single layer measured from the ground to 1.602 m (shoulder height of Dutch male, tallest European population)
- Monocular vision through respective windows (see Figure 25).

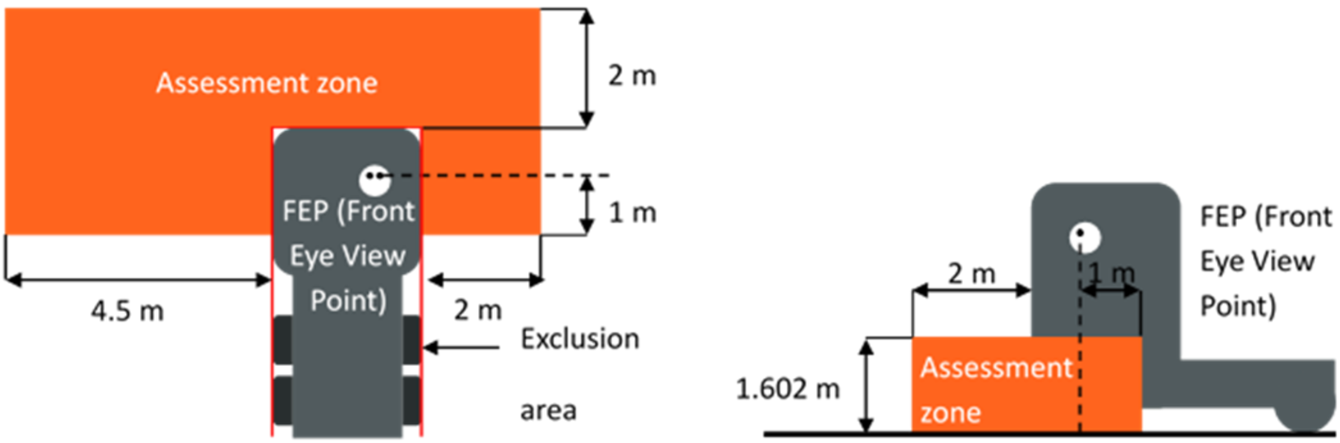


Figure 24: LDS and TfL DVS assessment zones. Diagram adapted from (Summerskill, et al., 2018)

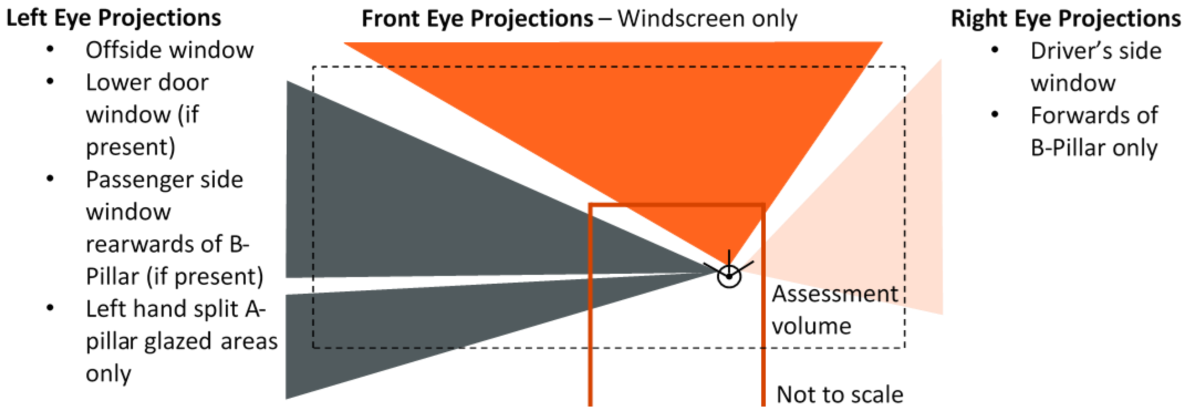


Figure 15: Eye point projections through daylight openings. Diagram adapted from (Summerskill, et al., 2018)

- Vehicle Set up: key changes include;
    - The driver's seat must be occupied by a driver with a mass of 75 kg;
    - The specified tyres should be at their minimum available ETRTO diameter for the tyre profile and tread type specified at the point of purchase.
- Method involves calculating the non-visible volume of the assessment zone.

5.1.5.2 Relevance to M_3 category vehicles and project

The HGV Direct Vision Standard sets out a method of scoring the level of direct vision provided to the driver of an HGV. Using this scoring scheme, TfL can limit certain vehicles from entering specific areas with a high concentration of VRUs and improve overall HGV safety standards by setting a minimum star rating safety standard. The scoring method will also benefit operators who can use this to make better informed decisions when purchasing vehicles to add to their fleet. In the future the DVS Protocol could be adapted to also include buses.

The inner edges of the DVS assessments zones run parallel to the sides and front of the vehicle (see Figure 24). Any object within these boundaries fall in to an exclusion area and are not included in the score. This may prove problematic for future vehicles with a rounded cab profile as it leaves the safety critical front corner regions in an unassessed zone. It is recommended that the Bus Vision Standard protocols are updated to reflect the changes made in the LDS and TfL HGV DVS as it is likely to be adopted, or used as a basis, for a future M_3 category vehicle direct vision regulation. Assessment zone boundaries may require further development to future proof the protocol.

5.1.6 TfL Blind Spot Safety System Test Protocol

5.1.6.1 Summary of regulation and tests

The Blind Spot Safety System Test Protocol, developed by TfL (TfL, n.d.), is an independent test and evaluation method for assessing the potential for blind spot safety systems.

The purpose of the protocol is to help inform HGV operators which blind spot safety devices are most effective at reducing VRU casualties during low speed manoeuvring. This is achieved by testing and then scoring the system using a five-star scoring scheme. The protocol is applicable to all goods vehicles with a maximum mass exceeding 7.5 tonnes and focuses on four main areas of technology:

- **Field of view aids:** These are devices which provide single additional indirect views (e.g. Camera Monitor Systems with one camera and one monitor) and systems that provide a single 360° composite birds eye view based on multiple devices (e.g. Cameras and/or other sensors). This does not include direct view (what a driver can see out of the windscreen or windows or indirect vision provided by mirrors);
- **VRU proximity warning to driver:** A type of warning issued to the driver any time a VRU is detected within a defined distance of the front or side of the vehicle;
- **VRU collision warning to driver:** A warning that is issued to the driver if the system calculates that a collision between a nearby VRU and the HGV is likely. The system will not warn the driver of the presence of a VRU in close-proximity if the trajectories of the vehicle and the VRU are such that a collision is not imminent. In some cases, a proximity warning can act as a collision warning in certain circumstances
- **Motion inhibit system:** This type of system prevents a vehicle from moving off from rest if it detects a VRU is at risk of collision in front of the vehicle. This can be achieved through intervention in throttle, gear selection or braking functions. This type of system must be approved for use by the Original Equipment Manufacturer (OEM) of the vehicle.

The protocol requires after-market systems to be installed and tested on a standard rigid category N_3 test vehicle with a tipper body, a maximum permissible mass of 32 tonnes, 4 axles (2 front (steered) and 2 rear) and a wheelbase between 6.5 – 7.5 m. For an OEM system, the rating shall apply to the vehicle and to any other models that share a similar configuration (two different tridem tippers with a lifting tag axle may get the same scores). A system fitted by a dealer may be tested either as an integrated system for the vehicle (OEM option) or as an after-market device fitted to a standard test vehicle. The system must be installed according to the manufacturer's recommendations.

In either case, the test, or supplied, HGV must have road legal tyres which are rated (speed, size and load) and inflated to the manufacturers specification. The load space must empty, and the addition of test equipment and driver must not add more than 250 kg on to the vehicle.

A blind spot safety system may have a dual purpose (e.g. a CMS may also feed an audible sensor). A manufacturer may market the additional features outside the scope of this protocol.

Some systems may incorporate configurable settings which could improve the performance e.g. the sensitivity of proximity or collision warnings. If this is the case the system shall be set to the middle setting or to the next possible less sensitive setting if this is not possible.

The test requires the use of impactable dummies that recreate the LIDAR, Photonic Mixer Device (PMD), RADAR, ultrasonic and visual signature of a real VRU (pedestrians and cyclists). The default dummy is static, however if the supplier presents evidence the system requires arm or leg movement an articulated version of the dummy may be used instead. If the system can distinguish between pedestrians and cyclists, the cycle dummy should be used in the tests requiring a left turn manoeuvre.

The pedestrian dummy should be an EPTa adult pedestrian dummy as described in the Euro NCAP test protocol for AEB-VRU (Euro NCAP, 2019). The colour of any stiffening ropes must be light grey to avoid high reflectivity. The radar reflective characteristics of the pedestrian dummy should be like an equivalent sized person.

The pedal cyclist dummy should be an EBT adult bicyclist dummy as described in the Euro NCAP test protocol for AEB-VRU (Euro NCAP, 2019) The bicycles wheels must be in contact with the ground and rotate during the test.

For tests requiring a VRU (pedestrian) dummy to be in motion, a low-profile pulley or self-propelled platform shall be used. The distance between the lower edge of the VRU and the road surface shall be less than 25 mm, and the platform and VRU mounting system must not influence RADAR return.

The need for a system to be tested using different methods varies according to its characteristics and applicability to certain scenarios. The protocol focuses on two main scenarios: an HGV moving off from rest and an HGV making a left turn. The applications are shown below in Table 15.

Table 15: Test methods required for different system characteristics, table adapted from (TfL, n.d.)

	Collision Scenario	Test Method	Blind Spot Safety Applications			
			Field of View aid	Proximity Warning	Collision Warning	Motion Inhibit
Test Methods Required	Moving Off	Proximity	✓	✓	X	X
		Collision	X	X	✓	✓
	Left Turn	Detection in presence of clutter	X	✓	X	X
		HGV & VRU move off together	✓	✓	✓	X
		VRU undertaking an HGV	✓	✓	✓	X
		False Positive: Left Turn without VRU	X	✓	✓	X
		False Positive: HGV proceeds straight ahead	X	✓	✓	X
	Universal	Additional HMI	✓	✓	✓	✓
		Quality, durability and installation	✓	✓	✓	✓

Moving off from rest scenarios are designed to be representative of collisions where a VRU, typically a pedestrian, walks in front of a stationary HGV in an urban area and is hit as the HGV pulls away because the driver is unable to see them. The scenario is split into two tests: the close-proximity test and the collision test. These tests represent a VRU walking out in front of a stationary or moving HGV at a traffic signal. The collision test method is similar however the VRU is positioned 25% - 75% of the width of the HGV and remains stationary throughout the test. The test vehicle is accelerated to no more than 10 km/h. To avoid running over the VRU dummy, the HGV driver may apply manual braking as soon as a collision warning is issued.

Turning left scenarios are split into five sub sections to allow different aspects of the systems to be assessed:

- The **detection in the presence of clutter** test procedure assesses a system's ability to detect a VRU in the presence of environmental clutter (e.g. railings and advertising hoarding). The test simulates a VRU passing a stationary truck using a dummy which is positioned at two different lateral distances from the vehicle (0.6m and 1.5m).
- The **HGV & VRU moving off together** test procedure simulates a collision where an HGV and a VRU, typically a cyclist, start together from rest, move in parallel then collide as the HGV turns left because the cyclist is in the nearside blind spot. During the test, the HGV accelerates up to and remains at 10km/h and the VRU reaches a speed of 6.5km/h. Again, two lateral separations between the VRU and HGV (0.6m and 1.5m) are assessed.

- The **VRU under-taking an HGV** test procedure simulates a scenario where a VRU, typically a cyclist, is approaching the rear of a stationary HGV at a moderate speed. The HGV starts to accelerate as the cyclist runs parallel to the HGV. There is a collision when the HGV turns left because the cyclist is in the blind spot.
- The **false positive, left turn without VRU** test procedure involves the test vehicle accelerating to the test speed of 10 km/h and then steering so the centre line of the vehicle follows a 10 m radius. The nearside of the HGV l should be 1.2 m from the kerb line. No VRU is present during this test and the system should not trigger.
- The **false positive, HGV proceeds straight ahead** test procedure simulates a VRU travelling past an HGV on the nearside. Starting from the rest position, the test vehicle shall accelerate to its test speed in a straight line and the VRU dummy is accelerated to higher speed such that it subsequently passes the HGV. The system should not trigger.

The human machine interface (HMI), overall quality, durability and installation are assessed for all systems. These assessments are based on documentary evidence provided by the supplier or a demonstration rather than through a formal independent test. Each of the individual tests and assessments described in above paragraphs will produce a final score between 0% and 100%. Scores are then weighted based on the importance of the test scenario to produce an overall score. Warning systems and Field of View Aids are rated separately as shown in Table 16 and Table 17. A list of the score boundaries can be seen in Table 18.

Table 16: Weighting of results for warning systems, table adapted from (TfL, n.d.)

Assessment type (A)	Crash Frequency weighting (B)	Test	Test Weighting (C)	Metric type	Metric Weighting (D)	Max Score (E)*	Weighted Points available A*B*C*D*E	Weighted score (test score*A*B*C*D)
90%	53%	Moving off: priority	55%	Performance	75%	1	0.02	
				HMI	25%	1	0.07	
	47%	Moving off: collision	45%	Performance	95%	1	0.02	
				HMI	5%	1	0.01	
		Left turn 1: Detection in presence of clutter	10%	Performance	75%	1	0.03	
				HMI	25%	1	0.01	
		Left turn 2: Moving off together	30%	Performance	75%	1	0.10	
				HMI	25%	1	0.03	
		Left turn 3: VRU undertaking	40%	Performance	75%	1	0.13	
				HMI	25%	1	0.04	
		Left turn 4: False positive (no VRU)	10%	Performance	75%	0	0	
				HMI	25%	0	0	
		Left turn 5: False positive Test Vehicle straight ahead	10%	Performance	75%	0	0	
				HMI	25%	0	0	
5%		Additional HMI requirements				1	0.05	
5%		Quality, Durability & installation				1	0.05	
Total								
Final score (100*total weighted score/total points available) %								

Table 17: Weighting of results for tests of field of view aid, table adapted from (TfL, n.d.)

Assessment Type	Crash Frequency Weighting (B)	Test	Test Weighting (C)	Metric Type	Metric Weighting (D)	Max Score (E)*	Weighted Points available A*B*C*D*E	Weighted score (test score*A*B*C*D)
90%	53%	Moving off: proximity		Performance	50%	1	0.24	
				HMI	50%	1	0.24	
	47%	Left Turn 2: Moving off together	43%	Performance	50%	1	0.9	
				HMI	50%	1	0.9	
		Left Turn 2: VRU undertaking	57%	Performance	50%	11	0.12	
				HMI	50%	1	0.12	
5%		Additional HMI				1	0.05	
5%		Quality, duration and Installation				1	0.05	
Total								
Final score (100*total weighted score/total points available) %								

Table 18: Rating boundaries, table adapted from (TfL, n.d.)

Star Rating	Score Thresholds
1 Star	11% - 30%
2 Stars	31% - 50%
3 Stars	51% - 70%
4 Stars	71% - 90%

5.1.6.2 Relevance to M3 category vehicles and project

The Blind Spot Safety System Test Protocol is an independent test and evaluation method that was developed for assessing the potential benefits of fitting blind spot safety systems to HGVs. The purpose of the protocol is to help inform HGV operators which blind-spot safety devices are most effective at reducing VRU casualties during low speed manoeuvring by testing and then scoring the system using a five-star scoring scheme. The protocol could be adapted to assess the performance of such systems fitted to buses by ensuring the weightings are applicable to collisions involving buses.

5.1.7 Proposal for a UN Regulation on blind spot information systems

5.1.7.1 Summary of regulation and tests

Uniform provisions concerning the approval of motor vehicles with regard to the Blind Spot Information System (BSIS Reg) is a proposal for a future Blind Spot Information System (BSIS) regulation in development by BAST, the German Federal Highway Research Institute (UNECE, n.d.).

The regulation will apply to blind spot information systems fitted to N_2 and N_3 vehicles (other vehicle types may be approved at the request of the manufacturer). The proposal covers systems that inform the driver of a possible collision with a pedestrian or bicycle, travelling next to the vehicle, if the driver starts to apply steering in a direction that conflicts with the path of the bicycle. The BSIS is required to function between 1km/h and 30km/h (in the forwards direction) and give an information signal for all bicycles travelling between 5 km/h and 20 km/h. The system should not give an information signal for stationary objects that are not identified as pedestrians or cyclists.

The blind spot information should be noticeable by the driver and be provided by one of the following types of warning; haptic, optic or acoustic, with spatial indication about the direction of the bicycle. If the vehicle is equipped with a Class II or IV Camera Monitor System, the information signal may be displayed on its corresponding monitor.

The system must give the driver a constant yellow optical warning signal in the event of a failure. This signal should be displayed when the ignition switch is turned to the on position or when the ignition is positioned between on and start depending on which option the manufacturer designates as a check position (initial power on). This requirement does not apply to existing warning signals displayed in a common space.

If the BSIS is equipped with user-adjustable information timing, the test should be performed with the information threshold set at its latest setting. The target needs to be a full 3D representation of a real bicyclist and bike with rotating wheels that are synchronised to speed. Pedalling legs are not mandatory for this test.

The BSIS test should be constructed using cones and the bicycle dummy, marked out in the layout seen in Figure 27.

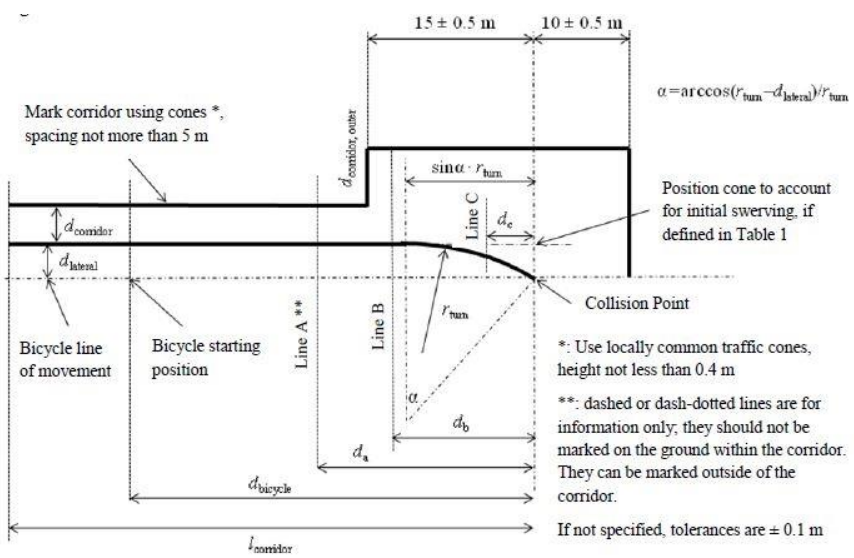


Figure 27: General test layout diagram (UNECE, n.d.)

The cyclist moves in a straight line and the HGV is driven through the corridor at the correct speed for the test, before commencing its turn in to the path of the bicycle (without direction indicators). The BSIS signal must be activated before the vehicle crosses a pre-determined point on the path prior to the point of collision.

5.1.7.2 Relevance to M_3 category vehicles and project

When implemented, the BSIS Reg will enforce a minimum performance level for cyclist detection systems and improve the driver's situational awareness in vehicles with approved devices installed. The scope of the proposal permits the approval of BSIS for vehicles other than N_2/N_3 but does not specifically apply to buses.

5.1.8 TfL Vehicle Operational Refurbishment Specification

5.1.8.1 Summary of regulation and tests

The TfL Vehicle Operational Refurbishment Specification outlines which components require replacing or repairing, and to what level of quality, when the interior of a bus, operated under the TfL franchise, reaches the end of its seven-year contract life cycle (TfL, 2013).

The document states both the nearside and offside wing mirror cluster casing must be yellow in colour to aid detection by VRUs and that no additional warnings or markings should be applied to them. Excluding this there are no further indirect vision related requirements tailored for TfL.

5.1.8.2 Relevance to project

Driver Assault Screens (DAS) are currently excluded from this document and as a result are not replaced unless noticeably damaged. Due to the importance of maintaining an adequate field of indirect and direct vision, DAS maintenance could be incorporated in to the glass maintenance clause which states “the bus refurbishment must replace all damaged glass and must be free of etching or any other visual disturbance in the glass”.

Other issues relating to DAS maintenance includes unintentionally marking the screen with limescale whilst cleaning it. Future changes to cleaning schedules or the adoption of TfL spot checks could eliminate this issue

6 Evaluation testing

6.1 Introduction

The purpose of this section is to describe the research performed within this project to evaluate the effectiveness of the solutions associated with the Direct Vision (DIR), Indirect Vision (IND) and Internal Obscuration (IOB) safety measures. Specifically, the following sections evaluate the impact of different bus front end designs on driver direct vision, different mirror configurations on driver indirect vision and the effect of internal obscurations on driver direct and indirect vision. The research described by these sections therefore provides further evidence to establish overall effectiveness values for the previously described DIV safety measure solutions.

6.2 Direct and indirect vision performance

6.2.1 Introduction

Sections 4 and 5 establish that there is currently a paucity in the specific evidence base relating to establishing the direct and indirect vision performance of buses across the TfL fleet. While the HGV sector has established that a large proportion of the fleet have poor levels of direct vision performance, the direct vision performance of buses has never been specifically researched before. Furthermore, no sector has attempted to quantify the differences in indirect vision performance between vehicles through using a standardised testing and assessment approach.

The aim of this research is to therefore investigate the current direct and indirect vision performance levels for a sample of the current TfL bus fleet. Specifically, this research aims, through a computer aided design (CAD) based approach, to evaluate the impact of different bus front end designs and mirror configurations on the direct and indirect vision of the driver to establish a combination that maximises the driver field of vision. The approach adopted for this research was based on the TfL Direct Vision Standard for HGVs, as previously defined by TRL (Robinson, et al., 2016) and which was, at the time of research planning, under review by Loughborough Design School.

6.2.2 Bus model set up

6.2.2.1 Bus Models

CAD data for five bus models (Models A-E) were received from a single manufacturer from the BSS project partners and included a mix of double and single deck buses for both previous and current generation bus front end designs. Different generations of bus models were selected because of the fundamental differences in bus front end design, particularly in the A-pillar region. Previous generation buses typically have box-type front ends where the A-pillars are located at the edges of the front end of the bus, whilst current generation buses typically have A-pillar located rearward of the front end of the bus and instead have curved “wraparound” windscreen sections at the edges of the bus front end. It should be noted that, Models D and E were variants of the same bus model with significant differences in bodywork, glazing and the mirrors fitted.

6.2.2.2 Bus model height

The bus model height was set to be the maximum possible ride height of the vehicle from the ground plane in its unladen state, with this representing a worst-case scenario for direct/indirect vision. This was provided by the BSS project partners for all bus models, with a height of 325 mm from the ground plane to the bus step used to maintain a consistent clearance between the bus models and the ground plane.

6.2.2.3 Glazing

All internal and external glazed areas were designated as transparent. All areas of glazing frit (mounting/bonding area), including fade off zones, were considered to be opaque and defined as an obstruction.

6.2.2.4 Other components

In order to minimise assessment times, all components that were deemed superfluous to affecting the field of vision of the driver were removed from the CAD model of the bus. The remaining components included:

- Exterior panels bounding transparent areas
- Exterior panels defining the extents of the vehicle to the front (e.g. bumper) and sides (e.g. wheel arches)
- Exterior elements occluding driver vision (e.g. mirrors, mirror arms, wipers etc.)
- Interior and exterior mirrored surfaces used to reflect the driver vision
- Interior elements that occluded driver vision (e.g. driver assault screen frame, dashboard, ticket machines, window seals/rubbers, trim panels on doors, A-pillars, B-pillars, grab handles, etc.)
- Key elements of the driver packaging (e.g. seats, steering wheel, armrest etc.)

6.2.2.5 Accelerator Heel Point

The Accelerator Heel Point (AHP) was defined, based on SAE J1516, SAE J1517 and SAE J1100, as a point at the intersection of the ball of the foot contacting the centre line of the undepressed accelerator pedal, while the bottom of the shoe is maintained on the pedal plane and in contact with the floor.

6.2.2.6 Driver field of view

The field of view of the driver was defined by ambinocular vision from two eye points (E_L and E_R), rotating about a neck pivot point (P), from which sightlines originate. The locations of points E_L, E_R and P and their ranges of motion are defined in relation to the reference eye point (E_{ref}), in order to define the driver field of view.

E_{ref} was located in line with the centre plane of the driver seat and offset from the AHP by 678 mm rearward and 1163.25 mm upward. The neck pivot point (P) was located

98 mm rearward of E_{ref}, whilst E_L and E_R were laterally offset from E_{ref} by ±32.5 mm (Figure 28).

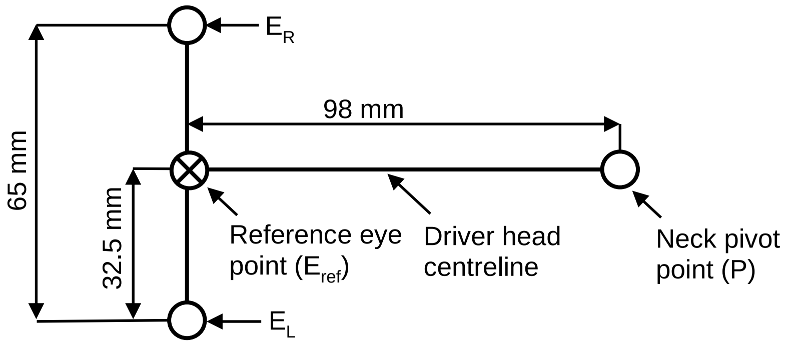


Figure 28: Definition of neck pivot point (P) and left and right eye point (E_L and E_R) positions relative to the reference eye point (E_{ref})

The horizontal rotation (β) of the neck pivot point, which determines the relative motion of the eye points, was defined by a maximum range of motion of ±90° rotation about the neck pivot point (P) (Figure 29). The horizontal rotation of both eye points (θ_L, θ_R) was defined by a maximum range of motion of ±30° rotation about each eye point (E_L and E_R).

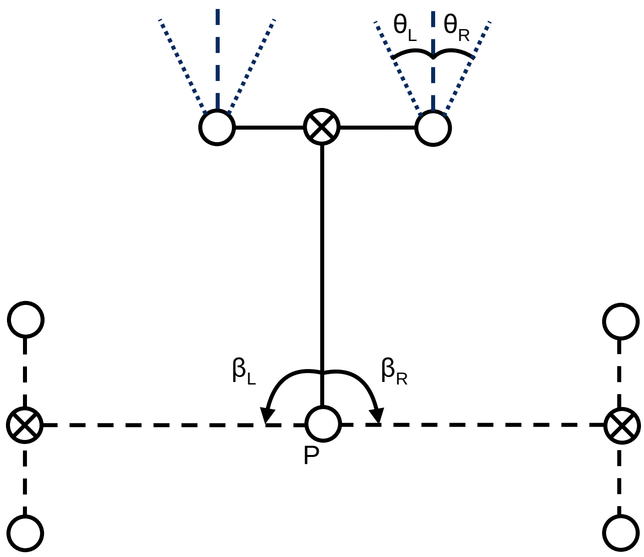


Figure 29: Plan view of horizontal neck point and eye point rotations

The vertical rotation of both eye points (θ_U, θ_D) was defined by a maximum range of motion of 45° upwards and 60° downwards about each eye point (E_L and E_R) (Figure 30). Vertical rotation about the neck pivot point was not included.

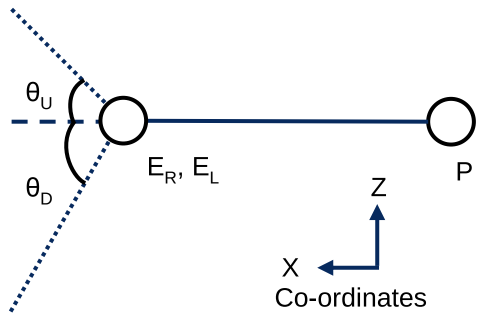


Figure 30: Side view of vertical eye point rotations

6.2.2.7 Mirrors

CAD models of the mirror surfaces, housings and arms were included, with the curved reflective surfaces of non-planar mirrors accurately represented. The mirror housings and arms were positioned in their designated in-use position, whilst the mirror surfaces were adjusted within the mirror housing to ensure visibility of the Class II field of vision zone defined in UN R46 (see Section 3).

Bus models A-C and E were fitted with standard planar Class II mirrors. Bus model D, however, was fitted with an Ashtree Vision & Safety Ltd CycleSafe Class II/VI mirror (see Figure 6).

6.2.3 Assessment zone set up

Based on the target populations defined in Section 2, three assessment zones were defined by this study for evaluating the direct and indirect vision performance of a bus:

- Forward Close Proximity Zone
- Rearward Close Proximity Zone
- Wide Angle Zone

The following sections define the boundary dimensions for these assessment zones.

6.2.3.1 Assessment zone height

Each assessment zone was formed by a volume formed between heights of 0-1.602 m from the ground plane.

6.2.3.2 Forward Close Proximity Zone

The dimensions of the Forward Close Proximity assessment zone, which is principally based on the Class V/VI field of vision zones specified in UN R46, are shown in Figure31 and described below:

- The foremost outer boundary of the assessment zone is defined by a plane parallel to the YZ plane and located 5 m in front of the foremost point of the vehicle structure.
- The nearside (left side) outer boundary of the assessment zone is defined by a plane parallel to the XZ plane and located 4.5 m outboard from the most lateral point of the nearside of the vehicle structure.

- The offside (driver side) outer boundary of the assessment zone is defined by a plane parallel to the XZ plane and located 2 m outboard from the most lateral point of the offside of the vehicle structure.
- The rearmost outer boundary of the assessment zone is defined by a plane parallel to the YZ plane and located 1.75 m to the rear of the reference eye point (E_{ref}).
- The inner boundary is defined by a curve located 0.3 m from the outermost point of the vehicle structure, when measured normal to the relevant vehicle structure (Figure 32).

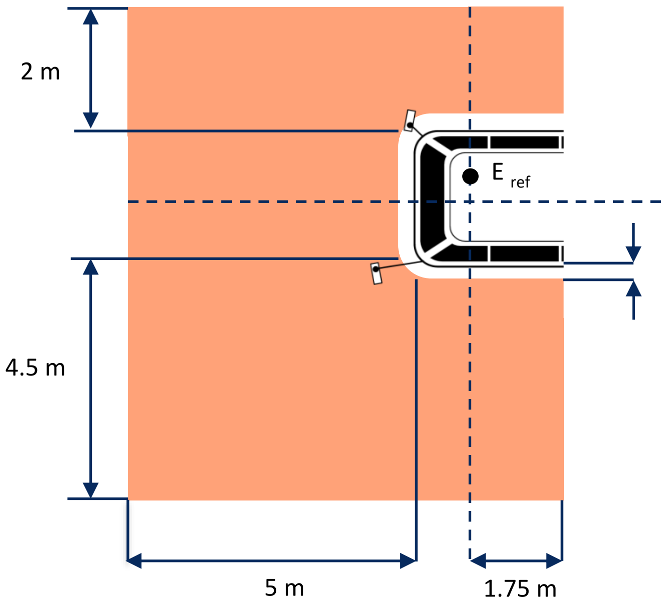


Figure 31: Plan view of Forward Close Proximity assessment zone

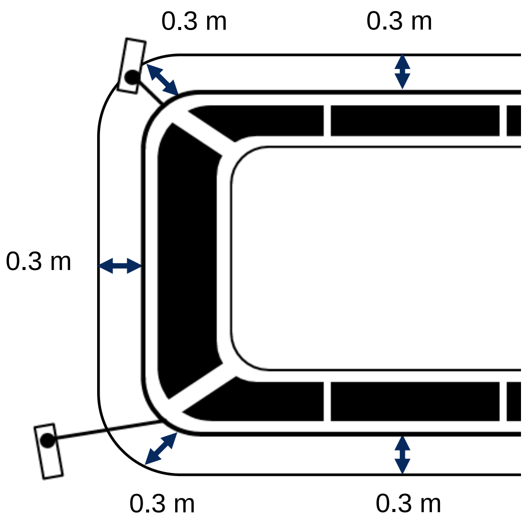


Figure 32: Illustration of profile for defining inner boundary of assessment zones

6.2.3.3 Rearward Close Proximity Zone

The dimensions of the Rearward Close Proximity assessment zone are shown in Figure 33 and described below:

- The foremost outer boundary of the assessment zone is defined by a plane parallel to the YZ plane and located 1.75 m to the rear of the reference eye point (E_{ref}).
- The nearside (left side) outer boundary of the assessment zone is defined by a plane parallel to the XZ plane and located 4.5 m outboard from the most lateral point of the nearside of the vehicle structure.
- The offside (driver side) outer boundary of the assessment zone is defined by a plane parallel to the XZ plane and located 2 m outboard from the most lateral point of the offside of the vehicle structure.
- The rearward outer boundary of the assessment zone is defined by a plane parallel to the YZ plane and located 5 m to the rear of the rearmost point of the vehicle structure.
- The inner boundary is defined by a curve located 0.3 m from the outermost point of the vehicle structure, when measured normal to the relevant vehicle structure (Figure 32).

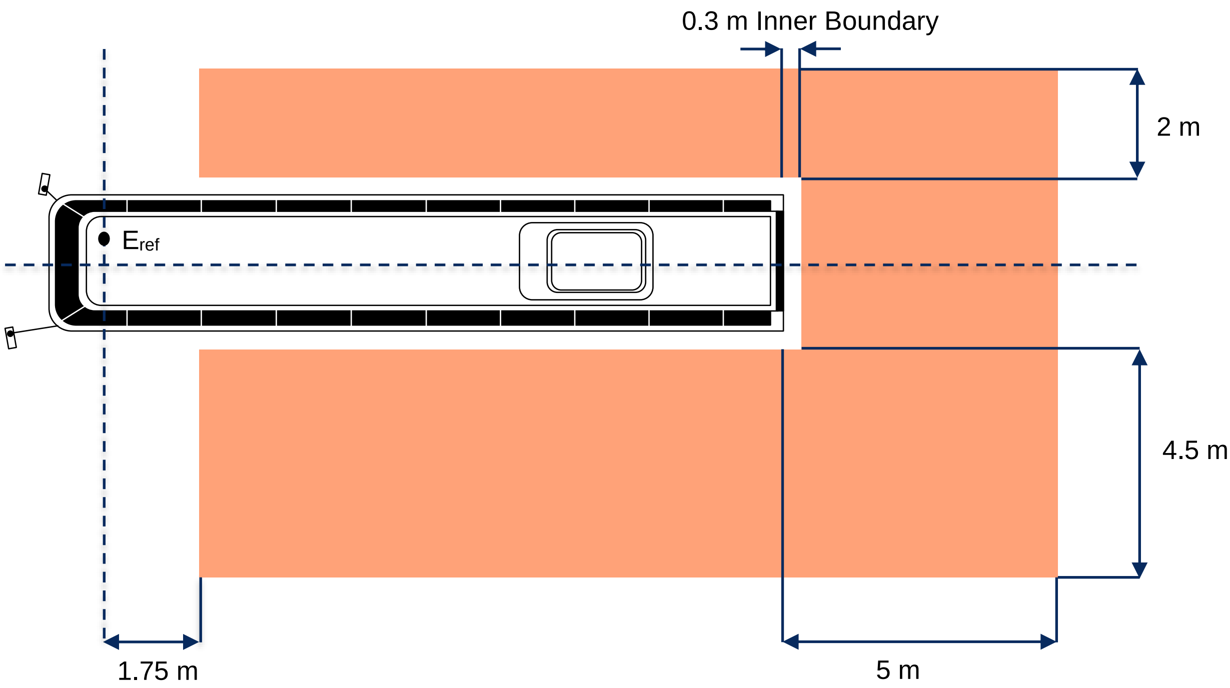


Figure 33: Plan view of Rearward Close Proximity assessment zone

6.2.3.4 Wide Angle Zone

The dimensions of the Wide Angle assessment zones, which are principally based on the field of vision zones specified for Class IV mirrors in UN R46, are shown in Figure 34 and described for each side of the vehicle below.

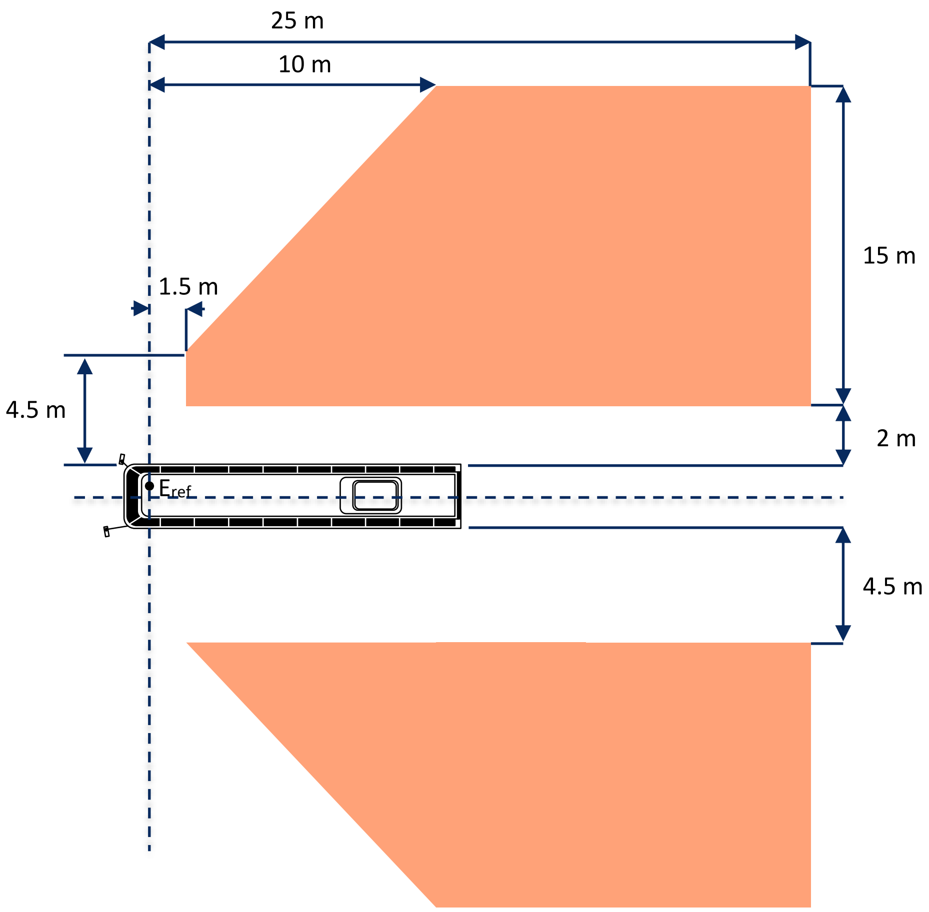


Figure 34: Plan view of Wide Angle assessment zone

Nearside (left side) wide-angle assessment zone:

- The rearmost boundary of the assessment zone is defined by a plane parallel to the YZ plane and located 25 m to the rear of the reference eye point (E_{ref}).
- The outer boundary of the assessment zone is defined by a plane parallel to the XZ plane, located 15 m outboard from the most lateral point of the nearside of the vehicle structure and extending from a point 10 m to the rear of the reference eye point (E_{ref}) to the rearward boundary of the assessment zone.
- The inner boundary of the assessment zone is defined by a plane parallel to the XZ plane, located 4.5 m outboard from the most lateral point of the nearside of the vehicle structure and extending from a point 1.5 m to the rear of the reference eye point (E_{ref}) to the rearward boundary of the assessment zone.

- The angled boundary for the assessment zone is formed by an angled vertical plane joining the foremost points of the outer and inner boundaries of the assessment zone.

Offside (driver side) wide-angle assessment zones:

- The foremost boundary of the assessment zone is defined by a plane parallel to the YZ plane, located 1.5 m to the rear of the reference eye point (E_{ref}) and extending from 2 m to 4.5 m outboard from the most lateral point of the offside of the vehicle structure.
- The rearward boundary of the assessment zone is defined by a plane parallel to the YZ plane and located 25 m to the rear of the reference eye point (E_{ref}).
- The outer boundary of the assessment zone is defined by a plane parallel to the XZ plane, located 15 m outboard from the most lateral point of the nearside of the vehicle structure and extending from a point 10 m to the rear of the reference eye point (E_{ref}) and the rearmost assessment zone boundary.
- The inner boundary of the assessment zone is defined by a plane parallel to the XZ plane and located 2 m outboard from the most lateral point of the nearside of the vehicle structure, extending from the foremost to the rearmost boundary.
- The angled boundary for the assessment zone is formed by an angled vertical plane joining the most lateral point of the foremost boundary and the foremost point of the outer boundary of the assessment zone.

6.2.3.5 Assessment zone elements

Each assessment zone was split into individual elements, approximately equal in both size and shape, with no single dimension exceeding 100 mm.

6.2.3.6 Assessment zone volume

The volume of all individual elements for each assessment volume was summed to form the assessment zone volume for the forward close-proximity zone (V_{FCP}), rearward close-proximity zone (V_{RCP}) and rearward wide-angle zone (V_{WA}).

6.2.4 Test Procedure

6.2.4.1 Sightline Projections

Sightlines were defined as lines representing the driver's line of sight from an eye point to an obstruction point, reflection point or a given distance. Sightline projections were generated for all neck pivot point and eye point angle (β, θ) combinations, where β was adjusted in increments of 10° and θ_L/θ_R were adjusted in 3° increments.

Each sightline was projected from a point of origin located at each eye point location assessed. Each sightline was increased in length to project along the eye point angle, until the sightline reached a 40 m length or intersected the following:

- an opaque vehicle structure defined as a mirrored surface (in this case, the sightline was not terminated and geometrically reflected by mirroring the angle of incidence relative to the normal of the mirror surface).

- an opaque vehicle structure not defined as a mirrored surface (in this case, the projection of the sightline was terminated at this point).

6.2.4.2 Determining visible volumes

All Forward Close Proximity assessment zone elements intersected by a sightline, but not reflected from a mirrored surface, were designated as visible through the direct field of vision of the driver. The volumes of the individual elements were summed to form the direct vision volume (V_D).

All Rearward Close Proximity assessment zone elements intersected by a sightline after reflection from a mirrored surface, were designated as visible through the indirect field of vision of the driver. The volumes of the individual elements were summed to form the indirect vision volume for mirrors in the rearward close-proximity zone (V_{IC}).

All rearward Wide Angle assessment zone elements intersected by a sightline after reflection from a mirrored surface, were designated as visible through the indirect field of vision of the driver. The volumes of the individual elements were summed to form the indirect vision volume for mirrors in the rearward wide-angle zone (V_{IW}).

Blind spot volumes (V_B) may be calculated for each assessment zone by subtracting the direct/indirect vision volumes from the relevant assessment zone volumes. All volumes were reported in cubic metres (m^3) to one decimal place.

Note that the indirect field of vision of the driver was not assessed for the Forward Close Proximity assessment zone. Similarly, the driver direct field of vision was not assessed for the Rearward Close Proximity and Wide Angle assessment zones.

6.2.4.3 Results Assessment Approach

Direct and indirect vision performance scores were calculated from this analysis using the below equations:

- Direct Vision Performance Score (DVS): $DVS = V_D/V_{FCP}$ %
- Close-Proximity Indirect Vision Performance Score (IVS_C): $IVS_C = V_{IC}/V_{RCP}$ %
- Wide-Angle Indirect Vision Performance Score (IVS_W): $IVS_W = V_{IW}/V_{WA}$ %

6.2.5 Evaluation of Results

6.2.5.1 Direct Vision Performance

The direct vision performance score of each bus model is shown below in Table 19. Between 89.1% and 91.5% of the Forward Close Proximity assessment zone is directly visible to the driver of each investigated bus model. This amounts to blind spot volumes of between 2.4 m^3 and 3.3 m^3 across all five bus models. Importantly, these results show that the direct vision performance of buses is excellent, particularly if compared to that of HGVs. Furthermore, this investigation shows that only marginal differences exist between different generations and types of bus model.

Table 19: Direct vision performance of bus models

Bus Model	Deck	Generation	Assessment Zone Volume (V_{FCP})	Direct Vision Volume (V_D)	Blind Spot Volume (V_B)	Direct Vision Performance Score (DVS)
A	Single	Previous	27.5 m^3	24.9 m^3	2.6 m^3	90.6%
B	Single	Current	30.7 m^3	28.0 m^3	2.7 m^3	91.2%
C	Double	Previous	30.6 m^3	27.4 m^3	3.2 m^3	89.7%
D	Double	Current	30.3 m^3	27.0 m^3	3.3 m^3	89.1%
E	Double	Current	27.8 m^3	25.4 m^3	2.4 m^3	91.5%

Figure 35 shows the direct vision blind spot zones associated with each bus model evaluated within this project. It is clear from these images that the blind spot zones associated with the direct vision performance of the current TfL bus fleet are likely to be minimal and that blind spots are similar in coverage between different generations of model and types of buses.

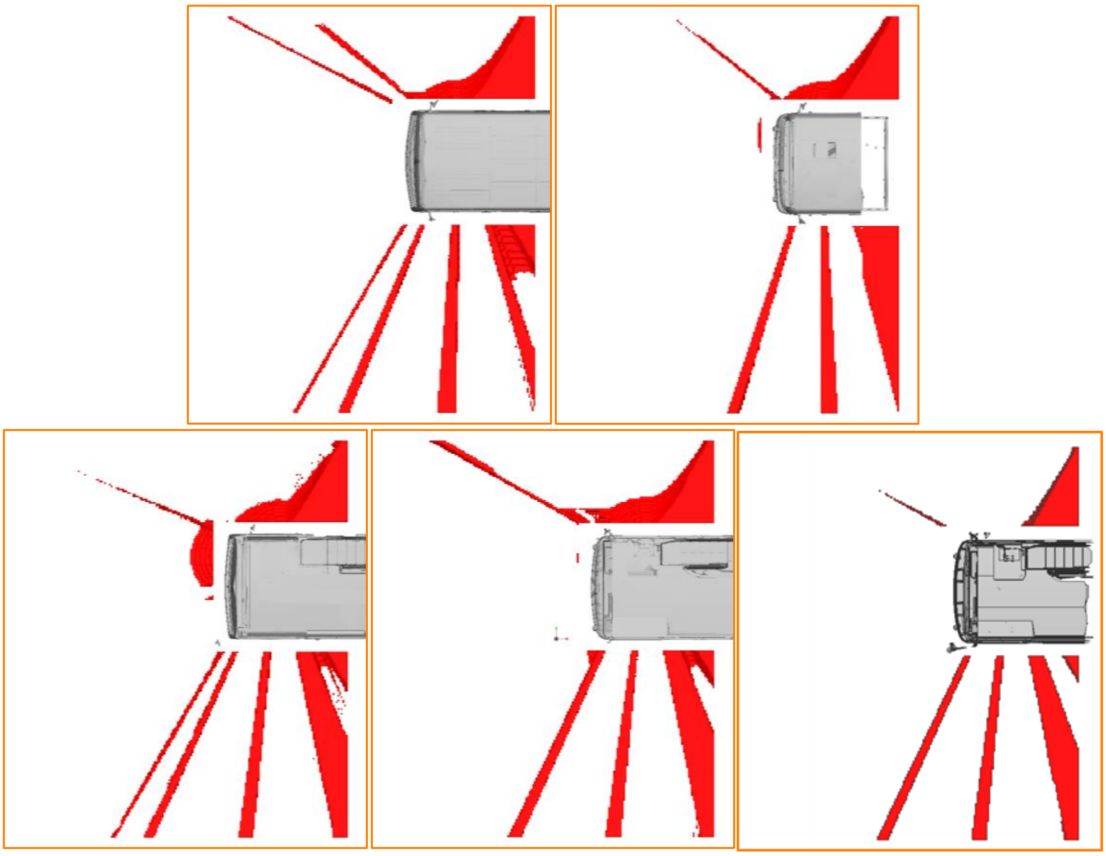


Figure 35: Direct vision blind spot zones in the forward close proximity assessment zone for each evaluated bus model. From top left: Bus Model A, Bus Model B, Bus Model C, Bus Model D, Bus Model E

When considering the differences between bus models, it was observed that the size of the obstruction and the distances between the eye points and larger obstructions were the key reasons for the variation. As expected, larger obstructions (e.g. A-pillars, bodywork, dashboard, etc.) created larger blind spots, whilst smaller obstructions (e.g. handles, windscreen wipers) created blind spots too small to intersect the assessment zone. Interestingly, this relationship with blind spot size was reversed for the distances to the obstruction. For obstructions of a similar size (e.g. the A-pillars), the nearer it was to the eye point, the smaller the blind spot. This is counter to previous research findings, which find that the nearer an obstruction is to the eye point the greater a blind spot it creates (Summerskill, et al., 2015). This is, however, primarily because of the use of more realistic ambinocular eye points and neck/eye point rotations in this study (as opposed to monocular vision from a small number of eye point positions), which better reflects how drivers look around the A-pillar in the real-world.

Two key driver blind spots were positioned rearward of the driver seating position on both the nearside and offside of the bus. These result in blind spots in a critical area that are also not regulated by UN R46 (Indirect Vision Devices). As cyclists typically manoeuvre in these blind spot areas around a bus, especially when overtaking and undertaking, these blind spots may therefore be concealing the presence of cyclists in close proximity to buses. Another important blind spot is the area towards the front nearside of the bus, where the previous generation of bus models have blind spots created by both the A-pillar and door frame, whilst the current generation of bus only have a blind spot created by a single pillar. Although there are clear differences, it is unknown how these differences affect outcomes. It is, however, an important area for detecting the key target population of pedestrians that cross in front of the bus from the nearside.

6.2.5.2 Indirect vision performance

The indirect vision performance scores of each bus model are shown below in Table 20 and Table 21, showing that between 26.6% and 30.3% of the Rearward Close Proximity and between 5.9% and 12.8% of the Wide Angle assessment zones are visible to the driver using Class II mirrors. This equates to a blind spot volume of over 100 m^3 associated with the Rearward Close Proximity zone and over 795 m^3 with the rearward Wide Angle zone. Furthermore, these results show that only relatively marginal differences exist between the different types of buses that use a similar mirror model.

These results are in direct comparison with the Bus Model D, which uses the Ashtree Vision & Safety Ltd CycleSafe combined Class II/IV blind spot mirror model. Through the use of curved reflective surfaces, this mirror provides the driver with an enhanced field of vision, with 76.1% and 69.9% of the Rearward Close Proximity and Wide Angle assessment zones being visible to the driver, respectively. The majority of the assessment zone volume that remained not visible to the driver was that directly to the rear of the bus and the most lateral aspects of the nearside assessment zones.

Table 20: Indirect vision performance of bus models in rearward close proximity assessment zone

Bus Model	Deck	Generation	Assessment Zone Volume (V_{RCP})	Indirect Vision Volume (V_{IC})	Blind Spot Volume (V_B)	Indirect Vision Performance Score (IVS_C)
A	Single	Previous	140.8 m^3	40.3 m^3	100.5 m^3	28.6%
B	Single	Current	150.4 m^3	39.9 m^3	110.5 m^3	26.6%
C	Double	Previous	154.9 m^3	46.9 m^3	108.0 m^3	30.3%
D	Double	Current	157.3 m^3	119.7 m^3	37.5 m^3	76.1%
E	Double	Current	157.3 m^3	46.4 m^3	110.9 m^3	29.5%

Table 21: Indirect vision performance of bus models in rearward wide angle assessment zone

Bus Model	Deck	Generation	Assessment Zone Volume (V_{WA})	Indirect Vision Volume (V_{IW})	Blind Spot Volume (V_W)	Indirect Vision Performance Score (IVS_W)
A	Single	Previous	910.9 m^3	96.1 m^3	814.8 m^3	10.5%
B	Single	Current	911.0 m^3	53.5 m^3	857.5 m^3	5.9%
C	Double	Previous	911.8 m^3	116.3 m^3	795.5 m^3	12.8%
D	Double	Current	911.2 m^3	636.6 m^3	274.5 m^3	69.9%
E	Double	Current	911.0 m^3	64.8 m^3	846.2 m^3	7.1%

Figure 36 shows the indirect vision blind spots in the Rearward Close Proximity zone associated with each bus and mirror model combination evaluated within this project. Figure 37 shows the indirect vision blind spots in the Wide Angle assessment zone associated with each bus and mirror model combination. It is clear from these images that, although the blind spot zones associated with indirect vision vary between bus models, the size of the blind spots are primarily dependent on the characteristics of the mirror model used.

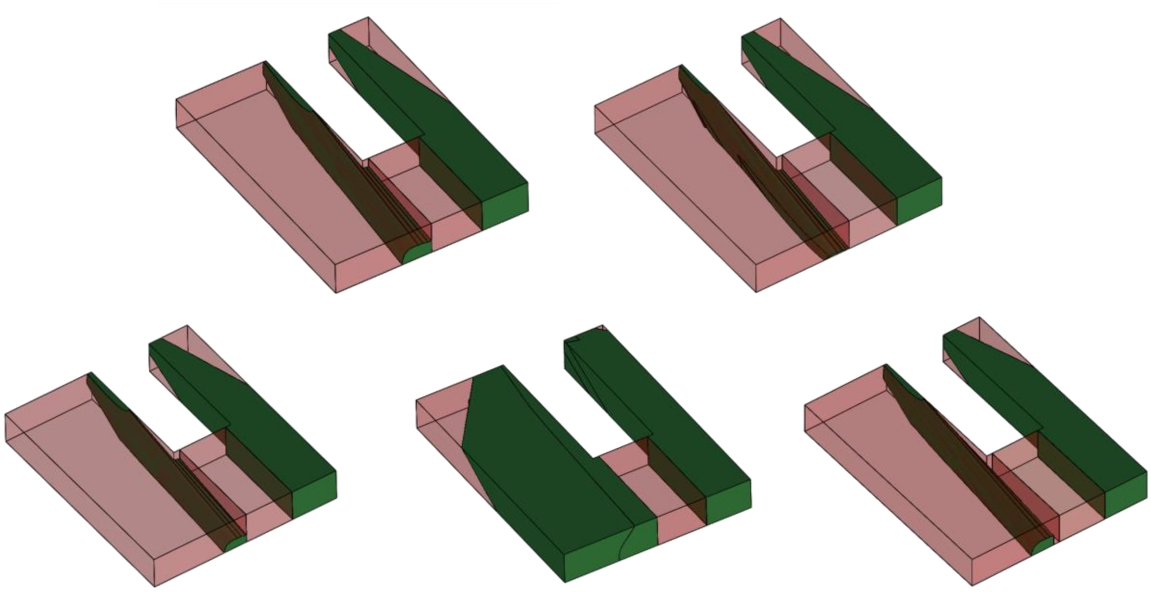


Figure 36: Indirect vision blind spot zones (pale red) in the Rearward Close Proximity assessment zone for each evaluated bus model; green is visible. From top left: Bus Model A, Bus Model B, Bus Model C, Bus Model D, Bus Model E

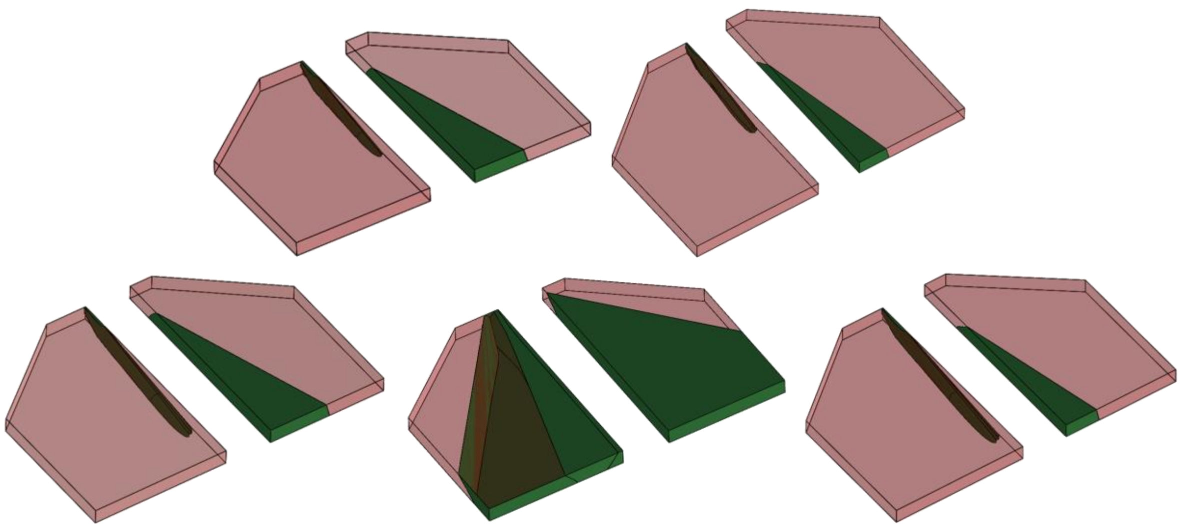


Figure 37: Indirect vision blind spot zones (pale red) in the Wide Angle assessment zone for each evaluated bus model; green is visible. From top left: Bus Model A, Bus Model B, Bus Model C, Bus Model D, Bus Model E

Importantly, these results show that, contrary to the excellent direct vision performance of buses, the current indirect vision performance of most buses across the TfL fleet is very poor, particularly if compared to indirect vision of HGVs. Fortunately, solutions exist that are capable of significantly improving the field of vision provided to the driver via indirect vision devices. It should also be noted that the Ashtree Vision & Safety Ltd CycleSafe mirror was capable of providing visibility to the driver in the key direct vision blind spots rearward of the driver seat on both sides of the bus – although this was not quantified by this study because it was not part of the assessment protocol and therefore outside of the scope of the research.

6.2.6 Conclusions

From these results it can be seen that the current direct vision performance of the TfL fleet is excellent, whilst significant improvements in the indirect vision performance of the fleet remain possible. The five investigated bus models were found to provide bus drivers with a direct field of vision comprising of ~90% of the area surrounding the bus front end. Any improvements to direct vision are therefore unlikely to lead to design changes that result in a significant reduction in VRU casualty rates, although such changes may affect the structural crashworthiness of the bus (due to the removal of structural material to increase the glazed area size), thus increasing the risks of injury to the bus driver and passengers. It is therefore important to ensure that the current excellent levels of direct vision performance are at least maintained within the future TfL bus fleet. This may be achieved by requiring a DVS score of 85%, which will ensure that any future changes to bus front end designs do not increase injury risks for either VRUs, bus drivers or bus passengers.

When considering the indirect vision performance of the current TfL fleet, the primary determinant of performance is the design of the indirect vision devices fitted to the bus. Devices that provide drivers with a greater indirect field of vision, without significantly affecting driver workload, should therefore be required to reduce the driver blind spots rearward of the driver position. The use of an Ashtree Vision & Safety Ltd CycleSafe mirror in this research indicated that, by installing this relatively low-cost and low-tech indirect vision device, the driver is able to see over 2.5 times the volume of the area directly surrounding the vehicle rearward of their position. As this device only provided drivers with a field of vision that comprised of 76.1% of the rearward close-proximity zone and 69.9% of the Wide Angle zone, further improvements in indirect vision performance are possible. It is therefore recommended that, in the short-term, mirrors that provide an increased field of vision relative to standard Class II mirrors should be required by the BSS, before introducing more stringent indirect vision requirements to further improve performance in the longer term.

When considering test and assessment approaches to evaluate the direct and indirect vision performance of a bus, it is recommended that a revised version of the approach used by this study is adopted. This approach, nominally the Bus Vision Standard, would provide a standardised approach to assessing the direct and indirect vision of a bus for a stated combination of bus front end design and indirect vision devices and provide a means to compare performance between current and future bus model designs.

Several key limitations exist for this research. Due to time and budget constraints, only five bus models, from a single manufacturer, and two mirror models were investigated. Future research should therefore consider evaluating the direct and indirect vision performance of a wider range of bus models, mirror and mirror arm combinations. The capability of indirect vision devices for removing driver blind spots in the Forward Close Proximity assessment zone was also not investigated in this study. This should, however, form a key element of the future Bus Vision Standard protocols. Finally, a major objective of this research is to align, wherever possible, with the HGV Direct Vision Standard (DVS) protocols currently being drafted by the Loughborough Design School on behalf of the TfL Freight Team. Whilst the methods undertaken in this project reflect the state-of-the-art at the time of planning, the latest release of the DVS shows important differences in the testing and assessment approach. The most notable differences were changes to the forward close-proximity assessment zone dimensions, the height of the assessment zones and the use of monocular eye points (instead of ambinocular). The future Bus Vision Standard protocols should reflect, wherever possible, the approach adopted in the final version of the HGV BVS.

6.3 Internal Obscurations

6.3.1 Introduction

When investigating the direct and indirect field of vision of a bus driver, it is important to consider blind spots caused by internal sources of obscuration or areas of optical distortion. It has been suggested that the Driver Assault Screen (DAS) can act as an immediate obscuration depending on its age, general condition, cleanliness and level of lighting. The following sections outline the test procedure developed and performed to determine the variation in transparency between DAS and the underlying causes.

6.3.2 Background

6.3.2.1 Driver Assault Screens (DAS)

The purpose of a Driver Assault Screen (DAS) is to act as a barrier between the driver and passengers in the event of violent interactions. DAS are typically manufactured from a clear polycarbonate and split in to two components: a forward and rear section. The rear section is integrated into the cabin door. Through this pane the driver, in most cases, is able to look through the windows within and to the rear of the service doors (a zone approximately equivalent to Class V field of vision) depending on the positioning of key structural components e.g. door and A-pillars. Some screen designs enable a view of the front nearside corner of the windscreen. A cluster of circular cut outs can often be found in the centre of the rear section to improve passenger to driver communication. The forward section covers the remaining gap from the door frame to the windscreen. The design of this section can vary significantly depending on which bus model it is installed in.

In general, the majority of DAS fall in to one of four main configuration families (see Figure 38 and schematic in Figure 40 overleaf):

- Configuration 1: Straight Forward
- Configuration 2: Curved Inwards
- Configuration 3: Angled Away
- Configuration 4: Curved Away

Figure 38: Variety of DAS configurations

Straight Forward configured DAS are typically found on older generation bus models. These are often heavily framed, partially or completely overlap internal and external mirrors and are hard to clean as porters must lean across to reach the extremities. Newer Curved Inward designs mitigate this issue by providing better access to the entire screen for cleaning and locating the central pillar of the frame to be in line with the A-pillar as the driver would view it.

Figure 39: Partial A-pillar overlap and reflectance through a Curved Inwards DAS (left). Unobstructed view of external and internal mirrors and area of optical distortion and reflectance caused by Curved Away DAS (right)

Angled Away and Curved Away DAS designs, such as the one found on the bus from Manufacturer A, are shaped to avoid overlapping and obscuring the mirrors from the drivers' point of view (see Figure 39). This can, however, result in an area of optical distortion and reflectance in the front nearside corner beside the A-pillar which, in certain environmental conditions (such as bright direct sunlight), may double the size of the blind spot created from the front nearside A-pillar (see Figure 39 and schematic in Figure 40). This is primarily due to the eye line of the driver aligning with the critical angle of the material that the driver is trying to look through (further information on critical angle contained in Appendix B).

6.3.2.2 Summary of Relevant Legislation

6.3.2.3 UN Regulation Number 43 (Safety Glazing)

To ensure the driver has a clear forward field of vision whilst looking through the DAS, the device must meet the minimum safety glazing transmittance criteria set out in UN Regulation Number 43 "Safety Glazing" (UN R43) (UN, 2017). UN R43 states the regular light transmittance for a windscreen and safety glazing (other than windscreens), required for the driver's forward field of vision shall be no less than 70%. In context to this piece of legislation "other safety glazing" is defined as all glazing situated in front of a plane passing through the driver's R point (seating reference point) and perpendicular to the longitudinal median plane of the vehicle through which the driver can view the road when driving or manoeuvring the vehicle (e.g. the Driver Assault Screen).

6.3.2.4 TfL Vehicle Operational Refurbishment Specification

There is no mention of DAS within the seven-yearly TfL Vehicle Operational Refurbishment Specifications (TfL, 2013). However, the document does state that the bus refurbishment must replace all damaged glass and must be free of etching or any other visual disturbance in the glass. This could be adapted for future versions to specify Driver Assault Screens.

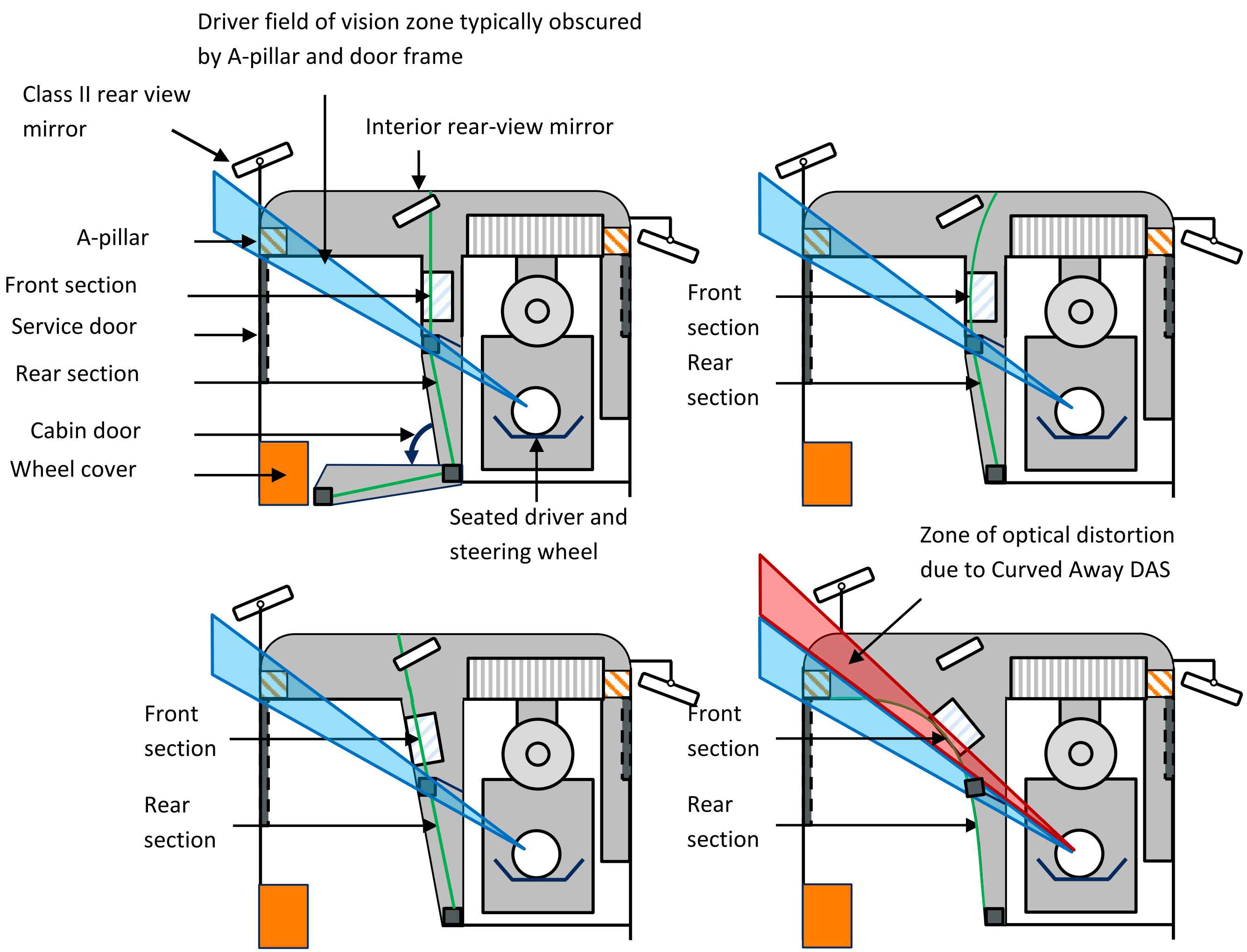


Figure 40: Straight Forward (upper left), Curved Inwards (upper right), Angled Away (lower left) and Curved Away (lower right)

6.3.3 Aims and objectives

The aim of this investigation is to determine the variation in DAS transparency levels across individual and families of DAS configurations to assess whether general wear and tear/damage, cleanliness and age impact levels of performance.

Objectives:

- Determine main types of DAS
- Determine the level of variation in DAS transparency
- Report on types of wear and tear and other forms of visual obscurations

6.3.4 Testing approach

The DAS transparency testing was split in to two phases. Phase 1 consisted of a single day of preliminary testing, which took place at two bus depots and involved:

- Gauging the variance in DAS transparency using material transmittance as a measure;
- Testing initial transmittance measuring methods; and
- Collecting useful information to inform the future development of the method for Phase 2.

Outcomes included the key points to measure, how to best measure the DAS and methods to prevent test area contamination (e.g. wearing cotton gloves to prevent adding to the finger prints already on the screen). The results from Phase 1 were only used to inform the test methods and were not used in the following evaluation.

Phase 2 involved four days of transmittance testing at two depots. The depots were selected because they are situated close together (operating in the same area) and have a large number and range of bus models at each site. To ensure that a broad range of DAS designs were assessed, the bus models were grouped together into the four DAS configurations (see Table 22). To represent the current TfL fleet, samples were taken from legacy vehicles (still in limited use), current models and new vehicles which will soon be in operational service with TfL.

Table 22: Phase 2 DAS sample size and composition

DAS configuration	Number of buses tested	Bus Model/s
Straight Forward	3	A
Curved Inwards	14	B, D, E, F
Angled Away	9	C, G
Curved Away	4	H

The wide range of DAS designs and bus cab layouts assessed meant it was not possible to select points based on their horizontal and vertical distance from a key edge or corner. A forward and rear section grid system was devised to ensure test points could be taken from equivalent regions allowing for comparisons between the various bus models. The number of columns and rows were based on which key vision zones could be seen by the driver.

A grid system was applied to the forward and rear section of the DAS. In most cases;

- The forward section was split in to nine zones (3 x 3 grid)
- The rearward section was split in to six zones (2 x 3 grid)
- The point of origin, with coordinates (0, 0), was always taken as the bottom right corner of the particular section (front or rear)
- The worst case test point, as determined by the test technician, was selected for measurement in each grid region. Examples of this include:
    - Scratching and chips
    - Finger marks and smudges
    - Limescale and streak marks due to cleaning products and technique
    - Fading (UV exposure)
    - Outer film layer peeled off DAS

If a grid region was categorised as clean, a random point was selected for testing. Up to an additional three points were marked on to the screen if the DAS overlapped with internal or external mirrors. A tintmeter[3] was used to record transmittance values at each test point. The two sensors of the tintmeter were placed on either side of the glass/material of the DAS.

Test data collected included; test point coordinates, a brief description of the test point (was it clean, scratched etc.), test point transmittance value (%), time since last clean, DAS age and a photograph (if the condition of the point was deemed important). Secondary factors were also described in cases where it was deemed to potentially be significant and included any environmental conditions that could have impacted transmittance (e.g. sunlight or low ambient light levels due to buses being parked very close together).

Initial findings from Phase 1 indicated that the repeatability of the transmittance value, when measuring the same point multiple times, was approximately ± 0.3%. As a result, it was decided to measure each test point only once during Phase 2 and round the value to one decimal place. To ensure consistency whilst measuring the point, the tintmeter was kept in position for 20 seconds and was calibrated between buses and after any knocks.

6.3.5 *Evaluation of results*

6.3.5.1 Key findings

Over the course of the Phase 2 testing, 639 test points were measured across 30 DAS and eight bus models. The key findings for each model show minimal variation in mean DAS transmittance in all but two of the bus models assessed; Bus A and Bus F (see Figure 41).

The lowest average transmittance levels were recorded on Bus A due to a high level of tinting in the rear DAS section. The second outlier, Bus F, featured many small, but almost opaque, stickers on its DAS. For the purpose of this section, all transmittance

[3] TintMan, Turnkey Instruments, Cheshire, UK

values linked to Bus A, and any Bus F grid sections with stickers, were therefore excluded from the following key findings (with the exception of Figure 41). These particular cases are discussed separately in Sections 6.3.5.2 and 6.3.5.3 respectively.

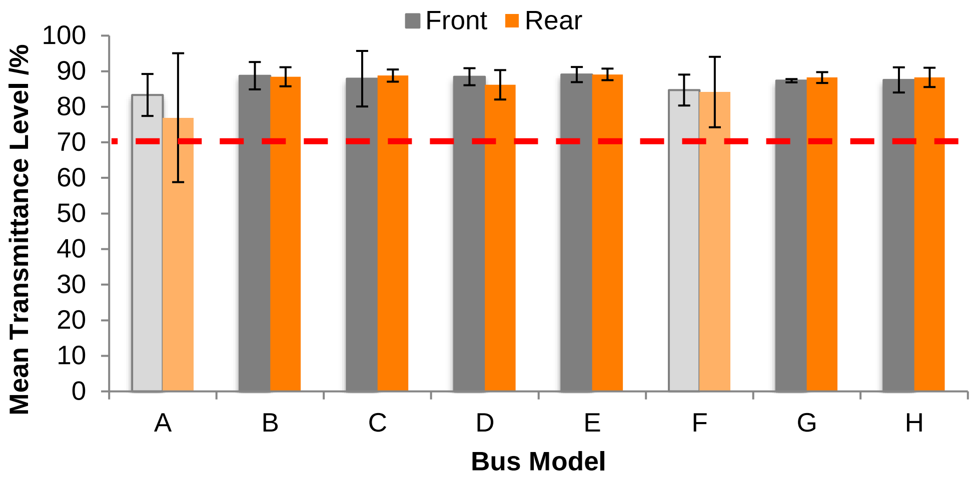


Figure 41: Mean transmittance levels for front and rear DAS for all models. Error bars represent the standard deviation from the mean (σ)

Feedback from drivers highlighted dirty screens, due to lack of cleaning or unsuitable cleaning equipment/technique, as a cause of visual obscuration. Cleaning schedule data was collected on each of the assessed buses to determine whether frequency of cleaning and time since last clean affect transmittance. Operational buses are given a frequent light clean and less frequent deep clean. The interval between these cleans vary between operators, with some operators performing deep and light cleans on 4-week and 8-week cycles and others on weekly and 13 weekly cycles, with the DAS cleaned in both the light and deep cleans. The results from this testing found that frequency of cleaning had no impact on DAS transmittance (Figure 42).

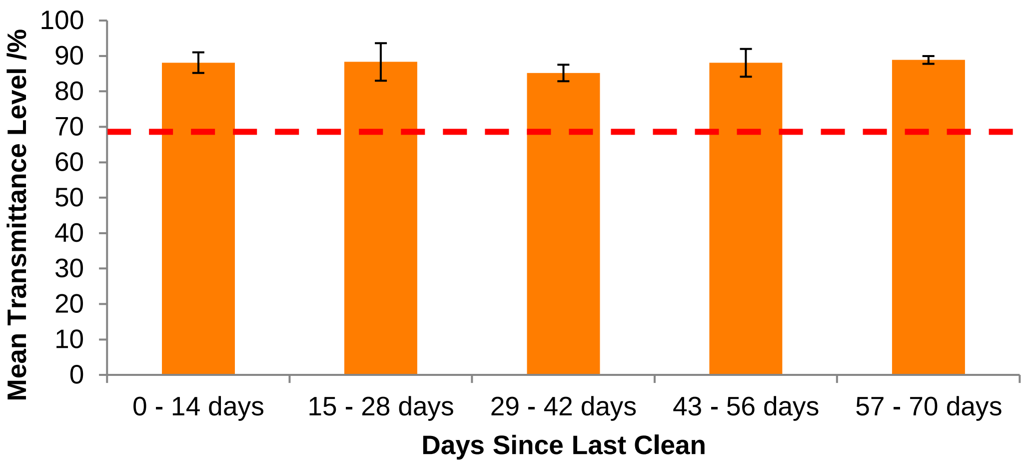


Figure 42: Mean transmittance levels compared to days since last clean. Error bars represent the standard deviation from the mean (σ)

It was also hypothesised that DAS transmittance decreases with age because of exposure to UV radiation from sunlight and due to a general increase in wear and tear. This was found not to be the case, with limited variation in transmittance across the age range of the DAS (see Figure 43).

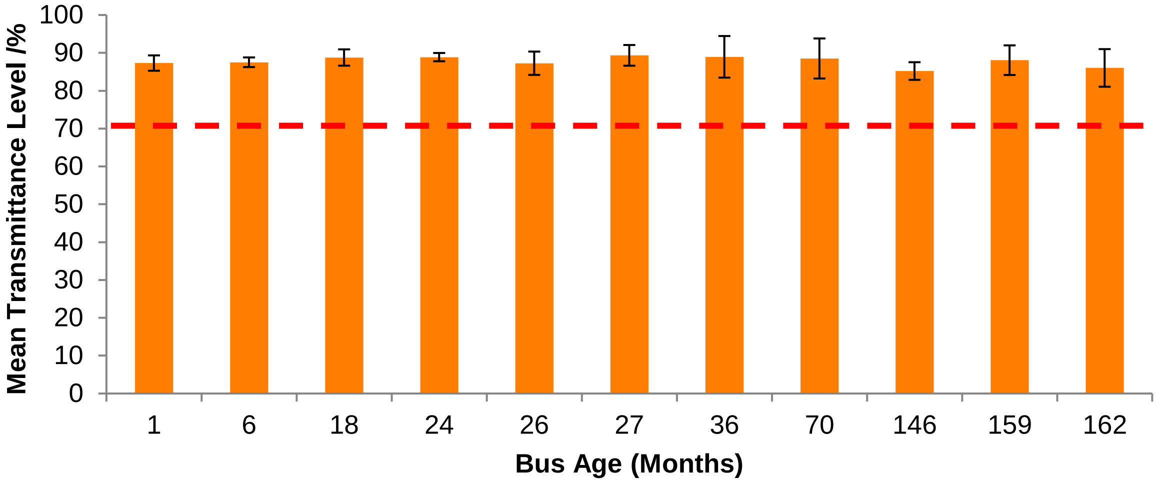


Figure 43: Mean transmittance levels compared to age of DAS. Error bars represent the standard deviation from the mean (σ)

The investigation found minimal variation in transmittance when comparing the results of different DAS configurations (Figure 44). It should be noted that, as the only Straight Forward DAS design tested was for Bus A, these results have been excluded from this analysis.

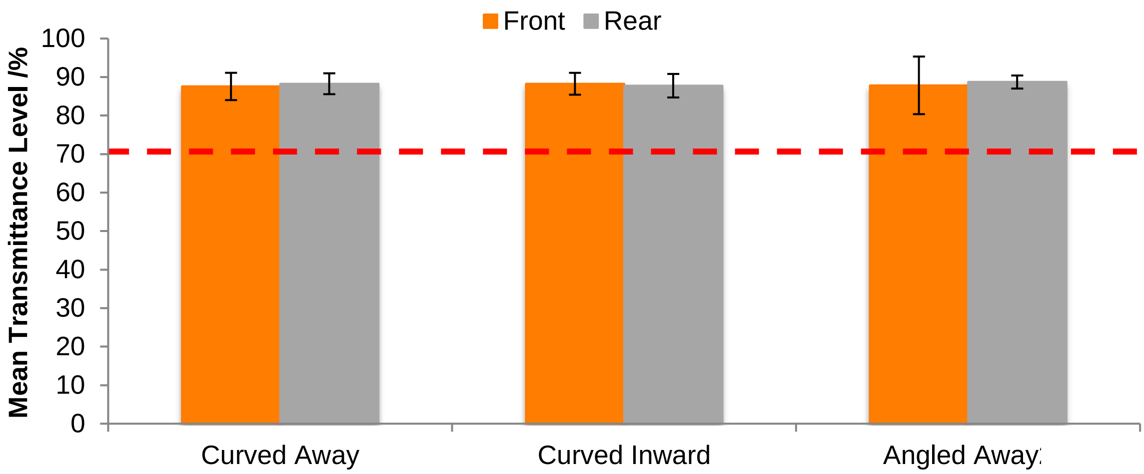


Figure 44: Mean transmittance levels compared between DAS configurations and front and rear DAS sections. Error bars represent the standard deviation from the mean (σ)

On all buses, obstruction to vision caused by reflections was observed to be a greater issue than DAS transmittance. During the testing it was observed that the level of reflection on curved screens was found to be far more visually obstructive than for non-curved DAS. Further information on the impact of reflections may be found in Appendix B.

6.3.5.2 Bus A: In-depth analysis

Whilst measuring the transmittance of the DAS for Bus A, it was found that zones 3, 6 and 9 of the rear section of the glazing had higher levels of tinting (see Figure 45).

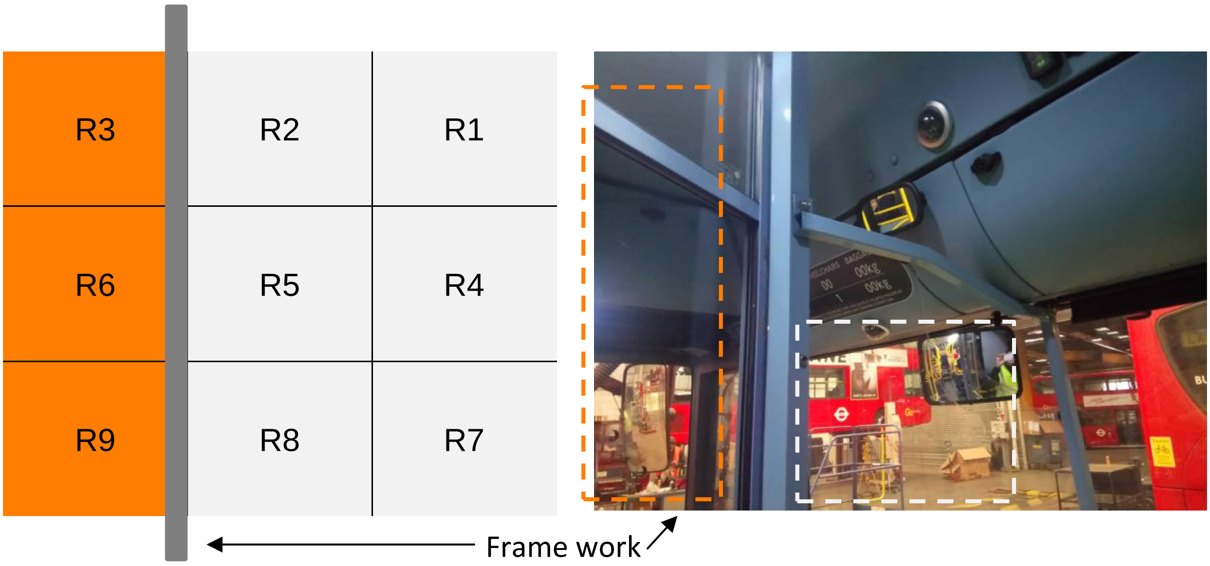


Figure 45: Schematic representation of the Bus A split rear section assessment grid looking out from cab (left) and a photograph taken from within the cab highlighting the difference in tint levels (right)

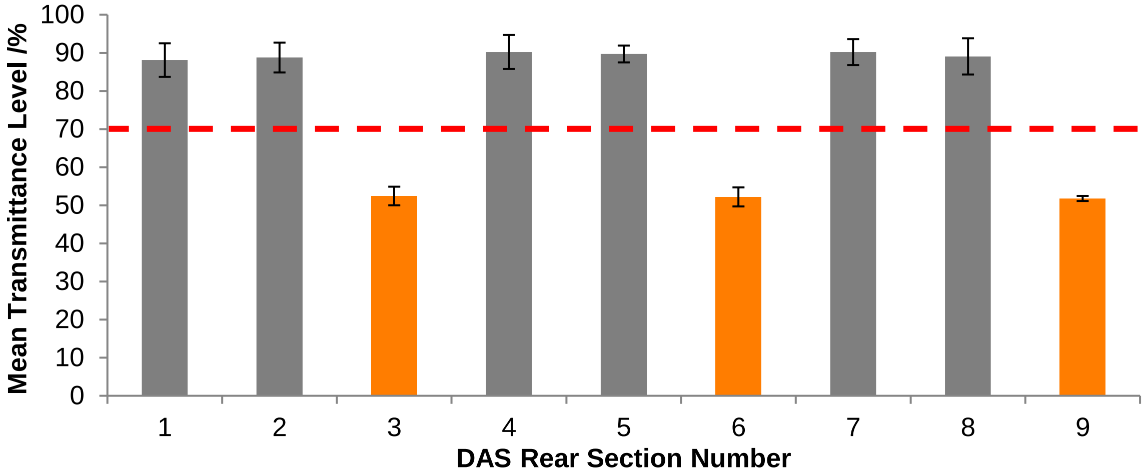


Figure 46: Mean transmittance levels for rear section of Bus A DAS. Error bars represent the standard deviation from the mean (σ)

The tinting in zones 3, 6 and 9 (see Figure 46) may reduce driver distractions such as nearby passenger activity or glare from sun. Despite their low transmittance, these zones are still compliant with UNR43 as they are located behind the forward field of vision of the driver and thus do not have to meet the 70% minimum transmittance requirement. It should not be a recommended feature for future vehicles, because the reduced rearward field of vision could have a negative impact on the ability of the driver to locate cyclists passing on the nearside or other road users moving in close proximity to the nearside of the vehicle.

6.3.5.3 Bus F: In-depth analysis

The low transmittance values associated with Bus F can be linked to two main reasons. Firstly, these vehicles were phased out of operational service and are now designated to infrequent special duties such as school trips and special events. It is not known whether they were used for training. They were not cleaned as often as their newer counterparts. Secondly a large amount of small, but almost opaque stickers and sticker residue was found on their screens (also linked to infrequent use) and so were selected as the worst-case point to measure in their respective grid regions. To gauge the impact these stickers had on Bus F DAS transmittance, the values related to the sticker readings were removed and compared to the original values with the stickers (see Figure 47 and Figure 48).

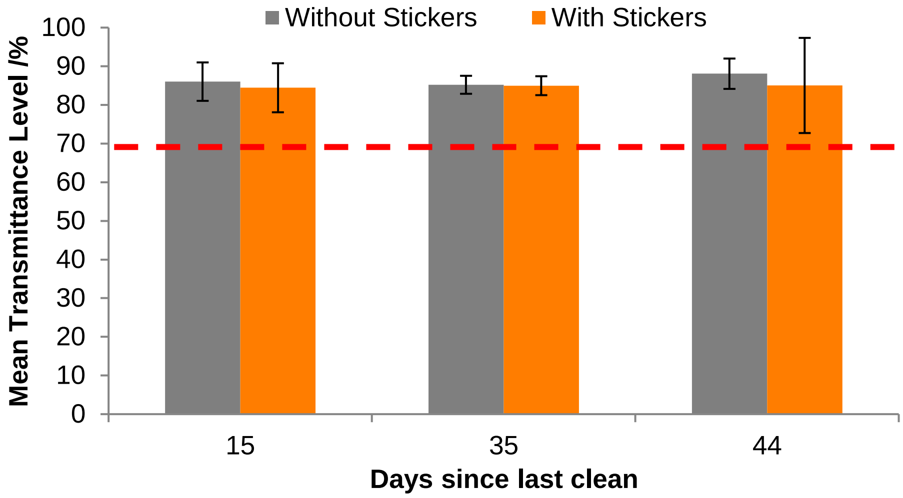


Figure 47: Mean transmittance levels compared between days since last clean and with/without data from sticker readings included for Bus F. Error bars represent the standard deviation from the mean (σ)

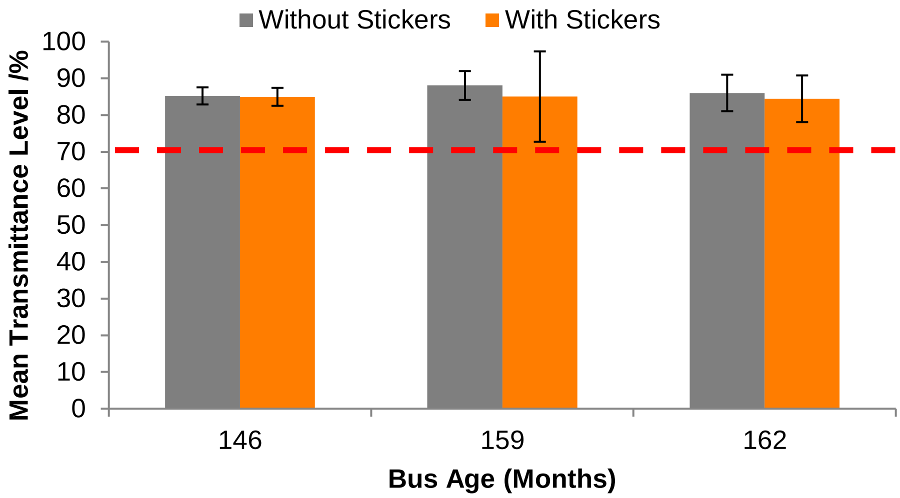


Figure 48: Mean transmittance levels compared between age of DAS and with/without data from sticker readings included for Bus F. Error bars represent the standard deviation from the mean (σ)

Removing theses values resulted in a 1-3% improvement in average transmittance for the front and rear sections in both graphs and a considerable improvement in the variability between results. These updated values were, however, still between 1-3% lower than the other bus models due to large scratches and smudges. It is presumed that if these vehicles had been in routine operational service, the DAS would not be left in this condition resulting in more comparable results to the other bus models.

6.3.5.4 DAS obscuration categorisation

Key terms were used to keep the point descriptions consistent. These were then grouped in to nine main categories for further analysis of the reasons behind the DAS obscuration and its effect on transmittance levels (see Table 23).

Table 23: DAS obscuration categorisation and incidence

Category	Details	Number of instances
Chips	Chip, chips, chips cluster	14
Cleaning related	Cleaning streaks, lime scale, spots, white spots	116
Mirror Points	External, internal, external - smudge large	62
No Transmittance Recorded	Cut out section, DAS does not overlap any internal or external mirrors, DAS does not overlap small internal mirror, not positioned correctly, not recorded, two columns	89
Outer film layer peeled off	Outer film layer peeled off	3
Random points (No damage)	No particular damage/obstruction	88
Scratches	Single/heavy/large/cluster of scratches	112
Smudge	Dirt, fingerprint, mark thick line, smudge, smudge large	128
Sticker	Residue, residue and light scratches, sticker	27

The mean transmittance levels associated with each DAS obscuration category were then analysed (Figure 49). It was found the sticker category had the largest effect on transmittance followed by areas where the outer film layer of the screen had peeled off. Cleaning related marks and finger prints were found to be the most common points to be selected on newer buses, whereas scratches and chips were more commonly considered worst case on older vehicles.

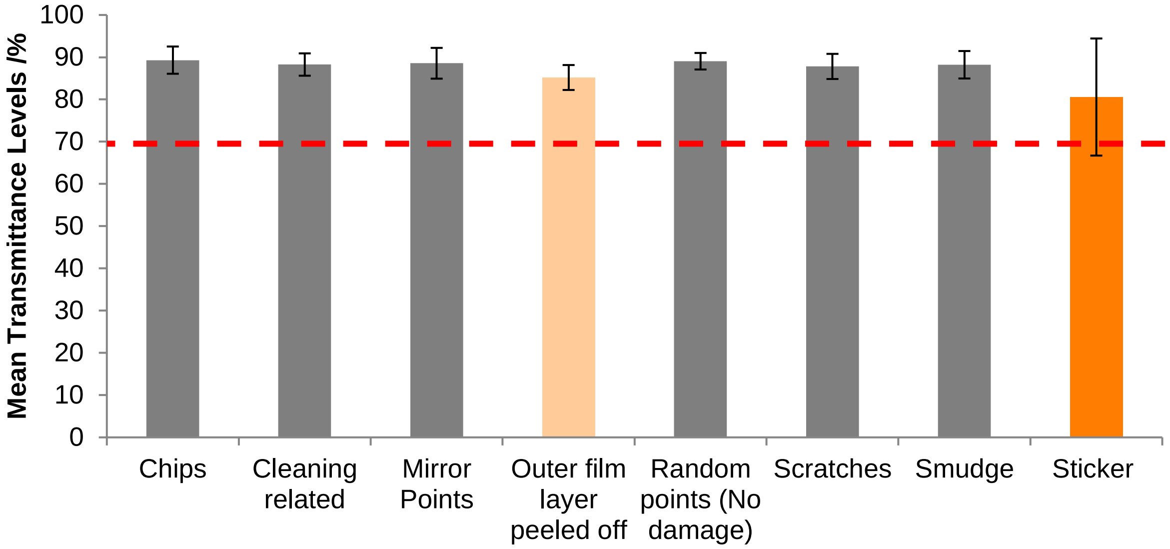


Figure 49: All models average transmittance of measuring point. Error bars represent the standard deviation from the mean (σ)

6.3.6 Conclusions

6.3.6.1 Key findings

The aim of this investigation was to determine the variation in transmittance across individual and families of DAS and assess the impact of general wear and tear/damage. This was achieved by grouping the assessed screens into four categories based on their design (Straight Forward, Curved Inward, Angled Away and Curved Away) and splitting the screens in a grid, before assessing transmittance levels at the worst-case point.

Overall, there was limited variation in DAS transmittance. Time since last clean, age of screen and DAS configuration were all found to have limited effect on transmittance levels. There were two main outliers within the results, these were; Bus A and Bus F. Bus A had the lowest average results, which were linked to heavily tinted glazing in the rear section of the DAS. Bus F had been designated to special duties and their screens were cleaned less frequently and had stickers present. Excluding the very small surface area covered by stickers and peeling DAS film, the defects found on DAS screens made limited difference to the overall transmittance.

Perhaps most importantly, internal reflections were found to be a higher priority issue than transmittance for DAS featuring a curved design and for designs that angled away from the driver. This was most noticeable for the Curved Away DAS, particularly where, towards the apex of the curved screen, the angle of incidence (from the driver's point of view) surpassed 74^{o}. At this angle the transmissive properties of the polycarbonate materials of the DAS start to reduce below the 70% transmittance threshold specified by UN R43 and so DAS reflectivity increases (see Appendix B). This causes an area of optical distortion and reflectivity approximately the same width of the A-Pillar (see Figure 39) in close proximity to the A-pillar. This increases the size of the blind spot in a key segment of the forward field of vision of the driver, which has an important link to the location where pedestrians would cross from the nearside of the bus. Appendix

B provides a further short analysis which aims to quantify the increase in blind spot volume in this region attributed to the DAS.

When considering BSS requirements, the surface of the DAS should therefore not be angled away from the driver eye line such that the angle of incidence at any point is greater than 74° (the angle at which polycarbonate would transmit less than 70% of unpolarised light). More information on this topic can be seen in Appendix B.

6.3.6.2 Key recommendations

Six key recommendations may be concluded following this investigation into Driver Assault Screen transmittance:

- Remove all risk of internal reflections obscuring the driver field of vision by removing the DAS entirely or by targeting potential blind spots critical to the driving task
- Encourage the fitment of DAS with a surface angled such that the angle of incidence from the driver eye line is no greater than 74° at any point on the DAS to reduce glare, distraction and blind spots.
- Avoid tinting any section of the DAS (including rearwards of driver forward field of vision) to prevent any unnecessary obscuration to VRUs to the nearside.
- Include replacing damaged DAS in the seven-year vehicle refurbishment cycle outlined within the TfL Vehicle Operational Refurbishment Specification
- Prevent the application of stickers on any section of the screen during operation
- Clean using a pH neutral solution to reduce the impact of Limescale deposits after cleaning.

These should be applied to all buses regardless of their operational route or use, including special duties, school trips, training etc.

6.4 Driver assault screen obscuration direct vision performance

An estimate of the effect that the reflections on the Curved Away DAS would have on the driver blind spot was made by using the test and assessment protocols to evaluate the direct vision performance of buses. This short additional analysis was performed to provide a better understanding of the effect of DAS obscurations on the direct vision of the driver, so that the effectiveness of the required DAS design improvements may be better estimated.

The method adopted by this study was to measure how the direct vision of Model E was affected by introducing an obstruction equivalent to the area of reflection observed for the relevant bus models. Please note, we were unable to source CAD models for the exact bus models affected by this issue, so a modified version of bus Model E was used as an alternative. The DAS was modified by introducing an obstruction to the driver sightlines in the DAS region affected by the reduction in transmittance and increase in reflectance (see light blue surface in Figure 50).

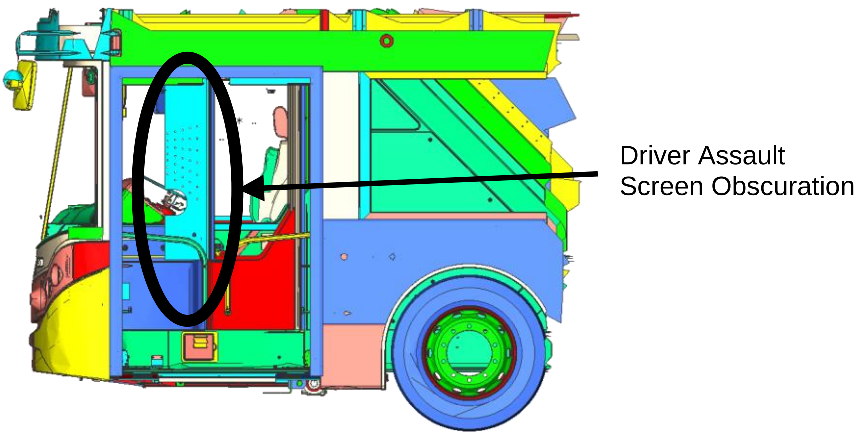


Figure 50: Illustration of driver assault screen obscuration (light blue) location

When comparing the differences between the direct vision performances of the two Model E buses, it is clear that there is a significant increase in the blind spot towards the front nearside of the bus (Figure 51). This is an important blind spot, because pedestrians often step out in front of buses from the nearside of the vehicle. As the increased driver blind spot volume is clearly large enough for a VRU to fit into, it may be presumed that the blind spot caused by the reflectance of the Curved Away DAS increases the risks of a collision occurring.

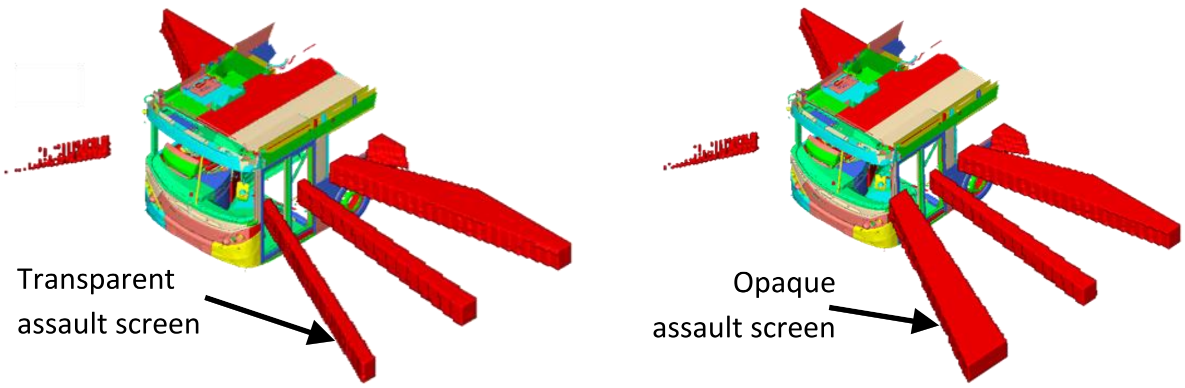


Figure 51: Comparison of the blind spots measured with a transparent (left) and opaque (right) assault screen

When comparing the effect of this blind spot, the direct vision performance score may be used to establish the increase in blind spot size relative to the size of the zone that pedestrians may be walking through when crossing from the nearside. As only the front-nearside aspect of the Forward Close Proximity zone is relevant to the view through the DAS, the direct vision performance score was calculated only for this part of assessment volume (DVS_{FN}) (Table 24). Importantly, these results show a reduction in the direct vision performance score of approximately 7.6%, which may be used to estimate the potential effectiveness of implementing DAS requirements that address this particular issue.

Table 24: Direct vision performance of Bus Model E both with and without DAS obstruction blind spot for front-nearside assessment zone only

Bus Model	DAS Blind Spot	Assessment Zone Volume (V_{FN})	Direct Vision Volume (V_{DFN})	Blind Spot Volume (V_B)	Direct Vision Performance Score (DVS_{FN})
E	With	10.78 m^3	9.69 m^3	1.09 m^3	10.1%
E	Without	10.78 m^3	10.40 m^3	0.38 m^3	3.5%

7 Cost-benefit analysis

7.1 Target population

The annual target population in 2018 estimated for all outcome severities (fatal, serious and slight casualties) relevant to the direct and indirect vision safety measure are presented in Table 25 below. Target populations were calculated for VRUs (pedestrians, cyclists and PTWs) only, as this is the population primarily affected by improvements in the direct and indirect vision performance of buses. The selection of appropriate target populations was performed to include the average annual number of VRU casualties involved in bus collisions in London, where the VRU was located in the fields of vision most relevant to the particular safety measure solution at the final point of intervention (see Section 2 for further information on target population calculations for each safety measure solution). All data was abstracted from the UK STATS19 road safety database.

Table 25: Estimated average annual target population in 2018 for the direct and indirect vision [DIV] safety measure solutions

Safety Measure Solution	Casualty Type	Outcome Severity		
		Fatal Casualties	Serious Casualties	Slight Casualties
Minimum DVS Performance Requirements	Pedestrians	2.6	12.7	53.9
	Cyclists	0.1	1.1	10.2
	PTWs	0	0.2	4.5
	Totals	**2.7**	**14.0**	**68.6**
Driver Assault Screen Design Requirements	Pedestrians	0.1	0.5	2.5
	Cyclists	0	0	0.2
	PTWs	0	0	0.1
	Totals	**0.1**	**0.6**	**2.8**
Minimum IVS Performance Requirements	Pedestrians	0.3	1.5	6.2
	Cyclists	0.2	3.5	28.3
	PTWs	0.2	1.3	13.4
	Totals	**0.7**	**6.3**	**47.9**
Enhanced IVS Performance Requirements	Pedestrians	0.3	1.5	6.2
	Cyclists	0.2	3.5	28.3
	PTWs	0.2	1.3	13.4
	Totals	**0.7**	**6.3**	**47.9**
Class II Mirror CMS Replacement	Pedestrians	0.2	1.5	5.7
	Cyclists	0.2	2.9	23.0
	PTWs	0.2	1.1	10.9
	Totals	**0.6**	**5.5**	**39.6**
Class IV Mirrors	Pedestrians	0	0	0.1
	Cyclists	0	0.6	5.2
	PTWs	0	0.2	2.3
	Totals	**0**	**0.8**	**7.6**
Class IV Camera Monitor System	Pedestrians	0	0	0.1
	Cyclists	0	0.6	5.2
	PTWs	0	0.2	2.3
	Totals	**0**	**0.8**	**7.6**

Safety Measure Solution	Casualty Type	Outcome Severity		
		Fatal Casualties	Serious Casualties	Slight Casualties
Class V (Blind Spot) Mirrors	Pedestrians	0.7	5.4	18.8
	Cyclists	0	0.7	5.5
	PTWs	0	0.1	2.0
	Totals	**0.7**	**6.2**	**26.3**
Class V (Blind Spot) Camera Monitor System	Pedestrians	0.7	5.4	18.8
	Cyclists	0	0.7	5.5
	PTWs	0	0.1	2.0
	Totals	**0.7**	**6.2**	**26.3**
Reversing Camera Monitor System	Pedestrians	0.1	0	0.4
	Cyclists	0	0	0.1
	PTWs	0	0	0.2
	Totals	**0.1**	**0**	**0.7**
360° Camera Monitor System	Pedestrians	2.9	14.2	60.0
	Cyclists	0.3	4.0	33.3
	PTWs	0.2	1.3	15.6
	Totals	**3.4**	**19.5**	**109.0**
Nearside VRU Information System	Pedestrians	0.8	5.7	20.5
	Cyclists	0.2	2.6	21.4
	PTWs	0.1	0.4	4.0
	Totals	**1.1**	**8.7**	**45.9**
Forward VRU Information System	Pedestrians	1.9	7.3	35.1
	Cyclists	0.1	0.4	4.7
	PTWs	0	0.1	2.5
	Totals	**2.0**	**7.8**	**42.3**

7.2 Estimates of effectiveness

The overall effectiveness values estimated for all outcome severities relevant to the direct and indirect vision [DIV] safety measure (fatal, serious and slight casualties) are presented in Table 26 below. A number of approaches were adopted to calculate the overall effectiveness values for each safety measure solution. Although greater detail regarding how these overall effectiveness values were calculated may be found in Section 4, the following paragraphs summarise the approaches that were adopted for calculating overall effectiveness values for each safety measure solution.

Firstly it was assumed all safety measure solutions would prevent incidents only, therefore all effectiveness values for casualty mitigation were assumed to be 0%. Overall effectiveness values for the minimum direct vision standard (DVS) performance requirements were also assumed to be 0%, due to the assumption that it would be possible for all current bus front-end designs to comply with the proposed DVS performance criteria (see Section X). When including driver assault screen (DAS) design requirements in the DVS requirements, it was estimated that between 5-10% of collisions would be prevented due to the driver having a 5-10% improvement in their field of vision in the region affected by curved-away DAS.

Overall effectiveness values for mirrors and camera monitor systems (CMS) were estimated based on the increased workload required by the driver to interpret the extra distorted and smaller images provided by each proposed mirror or CMS solution. Firstly, it was assumed that the driver would be able to view 100% of the relevant field of view through each mirror and CMS solution and drivers would always check mirrors and monitors in situations where VRUs were “at risk”. Based on research performed by Higashiyama & Shimono (2004) and Klinke *et al*. (2014), overall effectiveness values of 42-69% were then estimated to represent influence that image distortion and smaller image sizes would have on the time to interpret images provided by the addition of an extra mirror or monitor. These values were applied to all safety measure solutions involving a mirror or CMS viewing no greater than two fields of view; namely the Class IV mirror/CMS, Class V mirror/CMS and reversing CMS solutions.

For the 360° CMS, the overall effectiveness was estimated based on the increased workload required by the driver to interpret the stitched and plan view images displayed on the CMS monitor. As above, it was assumed that drivers would be able to view 100% of the relevant field of view and that they would always check the monitor in situations where VRUs were “at risk”. Overall effectiveness values of 16.7-34.0% were taken from previously reported overall effectiveness values for similar 360° CMS systems (Martin, et al., 2017). For the Class II mirror CMS replacement solution, overall effectiveness values was estimated based on the reduction in driver workload provided by the increased image size of the internally mounted nearside monitor relative to the nearside Class II mirror. Based on the research by Klinke *et al*. (2014) on the effects of screen size, overall effectiveness values of 6-16% were estimated to represent the influence that the larger image size would have on the time to interpret the images provided by the CMS monitors.

When considering the effectiveness of the minimum and enhanced indirect vision standard (IVS) performance requirements, the results of the direct and indirect vision evaluation tests were considered (see Section 6). In the case of the minimum IVS performance requirement, it was found that the driver would be able to view 5-15% more of the relevant space around the bus. With the enhanced IVS requirements, however, it was found that drivers would be able to see 75-85% of relevant space around the bus. Although it is unknown how exactly bus manufacturers would eventually achieve these fields of views, it was assumed that the driver would also experience an increase in workload due to the need to interpret the extra distorted and smaller images provided by the additional mirrors/CMS. Similar to the Class IV mirror/CMS, Class V mirror/CMS and reversing CMS solutions, correction factors of 42-69% were used to modify the overall effectiveness to represent this additional workload. When taking these correction factors into consideration, the overall effectiveness values of the minimum IVS performance requirements were 2-10%, whilst overall effectiveness values for the enhanced IVS performance requirements were calculated to be 32-59%.

The nearside VRU information system was assumed to position sensors along the entire nearside of the bus, whilst the forward VRU information system was assumed to locate sensors around the front end of the bus. 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). A 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 26: Estimated overall effectiveness ranges for casualties prevented for the direct and indirect vision [DIV] safety measure solutions

Safety Measure Solution	Casualty Type	Casualties Prevented		
		Fatal Casualties	Serious Casualties	Slight Casualties
Minimum DVS Performance Requirements	Pedestrians	0%	0%	0%
	Cyclists	0%	0%	0%
	PTWs	0%	0%	0%
Driver Assault Screen Design Requirements	Pedestrians	5-10%	5-10%	5-10%
	Cyclists	5-10%	5-10%	5-10%
	PTWs	5-10%	5-10%	5-10%
Minimum IVS Performance Requirements	Pedestrians	2-10%	2-10%	2-10%
	Cyclists	2-10%	2-10%	2-10%
	PTWs	2-10%	2-10%	2-10%
Enhanced IVS Performance Requirements	Pedestrians	32-59%	32-59%	32-59%
	Cyclists	32-59%	32-59%	32-59%
	PTWs	32-59%	32-59%	32-59%
Class II Mirror CMS Replacement	Pedestrians	6-16%	6-16%	6-16%
	Cyclists	6-16%	6-16%	6-16%
	PTWs	6-16%	6-16%	6-16%
Class IV Mirrors	Pedestrians	42-69%	42-69%	42-69%
	Cyclists	42-69%	42-69%	42-69%
	PTWs	42-69%	42-69%	42-69%
Class IV Camera Monitor System	Pedestrians	42-69%	42-69%	42-69%
	Cyclists	42-69%	42-69%	42-69%
	PTWs	42-69%	42-69%	42-69%
Class V (Blind Spot) Mirrors	Pedestrians	42-69%	42-69%	42-69%
	Cyclists	42-69%	42-69%	42-69%
	PTWs	42-69%	42-69%	42-69%
Class V (Blind Spot) Camera Monitor System	Pedestrians	42-69%	42-69%	42-69%
	Cyclists	42-69%	42-69%	42-69%
	PTWs	42-69%	42-69%	42-69%
Reversing Camera Monitor System	Pedestrians	42-69%	42-69%	42-69%
	Cyclists	42-69%	42-69%	42-69%
	PTWs	42-69%	42-69%	42-69%
360° Camera Monitor System	Pedestrians	17-34%	17-34%	17-34%
	Cyclists	17-34%	17-34%	17-34%
	PTWs	17-34%	17-34%	17-34%
Nearside VRU Information System	Pedestrians	38-40%	33-34%	33-34%
	Cyclists	42-46%	26-27%	26-27%
	PTWs	42-46%	26-27%	26-27%
Forward VRU Information System	Pedestrians	38-40%	33-34%	33-34%
	Cyclists	42-46%	26-27%	26-27%
	PTWs	42-46%	26-27%	26-27%

7.3 Fleet fitment and implementation timescales

Timescales were determined for both the retrofit and new build direct and indirect vision safety measure solutions to develop fleet fitment and policy implementation roadmaps for each potential solution (Table 27). The timescales were determined based on stakeholder consultations with bus manufacturers for first-to-market timescales and TfL for proposed timescales for policy implementation. Bus operators and Tier 1 suppliers contributed to establishing the estimates for current levels of fleet fitment and expected years to full fleet fitment after implementation for each solution. Please see stakeholder consultation report for further information on stakeholder feedback on fleet fitment and policy implementation timescales.

Table 27: Fleet fitment and policy implementation timescales for both the retrofit and new build direct vision [DIR] safety measure solutions

Safety Measure Solution	First to Market	Date Policy Implemented	Current Fleet Fitment	Full Fleet Adoption (yrs)	
				Retrofit	New Build
Minimum DVS Performance Requirements	2019	2021	100%	N/A	0
Driver Assault Screen Design Requirements	2019	2019	90%	N/A	7
Minimum IVS Performance Requirements	2019	2021	0%	2	12
Enhanced IVS Performance Requirements	2020	2024	0%	4	12
Class II Mirror CMS Replacement	2020	2021	0%	3	12
Class IV Mirrors	2019	2019	0%	2	12
Class IV Camera Monitor System	2020	2021	0%	2	12
Class V (Blind Spot) Mirrors	2019	2019	0%	2	12
Class V (Blind Spot) Camera Monitor System	2020	2021	0%	2	12
Reversing Camera Monitor System	2019	2019	90%	1	2
360° Camera Monitor System	2020	2021	0%	3	12
Nearside VRU Information System	2020	2024	0%	3	12
Forward VRU Information System	2020	2024	0%	3	12

7.4 Casualty benefits

Table 28 below summarises the estimated total change in the number of casualties expected in London during the period 2019-2031 by specifying the performance of new build buses for all direct vision safety measure solutions. Outcomes are then monetised to estimate the total value of these casualty reductions to society.

Table 28: Estimated total change in number and total value (NPV) of casualties over the 2019-2031 analysis period for the new build direct and indirect vision [DIV] safety measure solutions

Safety Measure Solution	Casualty Type	Number of Casualties (n)			Total Value (NPV) of Incidents (£M)
		Fatal Casualties	Serious Casualties	Slight Casualties	
Minimum DVS Performance Requirements	Pedestrians	0	0	0	0
	Cyclists	0	0	0	0
	PTWs	0	0	0	0
	Totals	**0**	**0**	**0**	**0**
Driver Assault Screen Design Requirements	Pedestrians	0.01-0.01	0.04-0.07	0.17-0.34	0.023-0.046
	Cyclists	0	0	0.02-0.04	0.002-0.004
	PTWs	0	0	0.01-0.01	0
	Totals	**0.01-0.02**	**0.04-0.07**	**0.19-0.38**	**0.025-0.050**
Minimum IVS Performance Requirements	Pedestrians	0.04-0.19	0.2-1.0	0.8-4.0	0.12-0.61
	Cyclists	0.04-0.18	0.6-3.1	5.0-24.8	0.27-1.35
	PTWs	0.02-0.12	0.2-0.8	1.6-8.0	0.10-0.51
	Totals	**0.10-0.48**	**1.0-4.8**	**7.5-36.8**	**0.50-2.47**
Enhanced IVS Performance Requirements	Pedestrians	0.44-0.81	2.2-4.1	9.2-17.1	1.40-2.61
	Cyclists	0.41-0.76	7.1-13.3	57.8-107.7	3.14-5.84
	PTWs	0.28-0.51	1.8-3.4	18.5-34.5	1.18-2.19
	Totals	**1.12-2.09**	**11.2-20.8**	**85.6-159.3**	**5.72-10.65**
Class II Mirror CMS Replacement	Pedestrians	0.07-0.18	0.5-1.4	2.0-5.4	0.27-0.72
	Cyclists	0.10-0.26	1.4-3.8	11.2-29.9	0.65-1.73
	PTWs	0.07-0.18	0.4-1.0	3.6-9.7	0.26-0.68
	Totals	**0.23-0.62**	**2.3-6.2**	**16.9-45.0**	**1.17-3.13**
Class IV Mirrors	Pedestrians	0	0	0.3-0.5	0.00-0.01
	Cyclists	0	2.4-3.9	20.6-33.8	0.82-1.34
	PTWs	0	0.5-0.9	6.3-10.3	0.21-0.35
	Totals	**0**	**2.9-4.8**	**27.2-44.6**	**1.03-1.70**
Class IV Camera Monitor System	Pedestrians	0	0	0.3-0.4	0.00-0.01
	Cyclists	0	2.0-3.4	17.8-29.2	0.70-1.16
	PTWs	0	0.5-0.8	5.4-8.8	0.18-0.30
	Totals	**0**	**2.5-4.1**	**23.4-38.4**	**0.89-1.46**
Class V (Blind Spot) Mirrors	Pedestrians	2.07-3.40	15.8-26.0	55.1-90.4	7.95-13.06
	Cyclists	0	2.8-4.5	21.9-36.0	0.92-1.51
	PTWs	0	0.2-0.4	5.4-8.9	0.13-0.22
	Totals	**2.07-3.40**	**18.8-30.9**	**82.4-135.3**	**9.00-14.78**
Class V (Blind Spot) Camera Monitor System	Pedestrians	1.77-2.91	13.5-22.2	47.1-77.3	6.79-11.15
	Cyclists	0	2.4-3.9	18.9-31.0	0.79-1.30
	PTWs	0	0.2-0.3	4.6-7.6	0.11-0.18
	Totals	**1.77-2.91**	**16.1-26.4**	**70.6-115.9**	**7.69-12.64**
Reversing Camera Monitor System	Pedestrians	0.05-0.09	0	0.22-0.36	0.10-0.17
	Cyclists	0	0	0.07-0.11	0.001-0.002
	PTWs	0	0	0.10-0.17	0.002-0.003
	Totals	**0.05-0.09**	**0**	**0.39-0.64**	**0.11-0.17**
360° Camera Monitor System	Pedestrians	2.88-5.87	14.1-28.8	59.6-121.5	9.15-18.66
	Cyclists	0.41-0.83	5.4-11.0	45.2-92.1	2.58-5.26
	PTWs	0.18-0.38	1.2-2.4	14.4-29.4	0.82-1.67
	Totals	**3.47-7.08**	**20.7-42.2**	**119.2-243.1**	**12.54-25.58**
Nearside VRU Information System	Pedestrians	1.45-1.51	9.0-9.0	32.5-32.5	5.04-5.15
	Cyclists	0.54-0.60	4.3-4.5	35.6-36.7	2.44-2.60
	PTWs	0.18-0.20	0.4-0.5	4.5-4.6	0.50-0.54
	Totals	**2.17-2.31**	**13.8-14.0**	**72.5-73.8**	**7.98-8.29**

Safety Measure Solution	Casualty Type	Number of Casualties (n) Fatal Casualties	Serious Casualties	Slight Casualties	Total Value (NPV) of Incidents (£M)
Forward VRU Information System	Pedestrians	3.44-3.59	11.6-11.6	55.6-55.6	9.58-9.85
	Cyclists	0.27-0.30	0.7-0.7	7.8-8.1	0.76-0.82
	PTWs	0	0.1-0.1	2.8-2.9	0.07-0.07
	Totals	**3.71-3.89**	**12.3-12.4**	**66.2-66.6**	**10.41-10.74**

Table 29 below summarises the estimated total change in the number of casualties expected in London during the period 2019-2031 by specifying the performance of retrofit buses for all direct vision safety measure solutions. Outcomes are then monetised to estimate the total value of these casualty reductions to society.

Table 29: Estimated total change in number and total value (NPV) of casualties over the 2019-2031 analysis period for the retrofit direct and indirect vision [DIV] safety measure solutions

Safety Measure Solution	Casualty Type	Number of Incidents (n) Fatal Casualties	Serious Casualties	Slight Casualties	Total Value (NPV) of Incidents (£M)
Minimum DVS Performance Requirements	Pedestrians	N/A	N/A	N/A	N/A
	Cyclists	N/A	N/A	N/A	N/A
	PTWs	N/A	N/A	N/A	N/A
	Totals	**N/A**	**N/A**	**N/A**	**N/A**
Driver Assault Screen Design Requirements	Pedestrians	N/A	N/A	N/A	N/A
	Cyclists	N/A	N/A	N/A	N/A
	PTWs	N/A	N/A	N/A	N/A
	Totals	**N/A**	**N/A**	**N/A**	**N/A**
Minimum IVS Performance Requirements	Pedestrians	0.07-0.36	0.4-1.9	1.6-7.7	0.23-1.18
	Cyclists	0.07-0.32	1.1-5.6	9.3-45.7	0.51-2.49
	PTWs	0.05-0.23	0.3-1.5	3.2-15.7	0.20-1.00
	Totals	**0.19-0.92**	**1.8-9.0**	**14.0-69.1**	**0.95-4.68**
Enhanced IVS Performance Requirements	Pedestrians	0.89-1.65	4.5-8.4	18.7-34.9	2.86-5.33
	Cyclists	0.81-1.51	14.1-26.3	114.7-213.6	6.24-11.62
	PTWs	0.56-1.05	3.7-6.9	38.0-70.7	2.42-4.50
	Totals	**2.26-4.21**	**22.4-41.7**	**171.4-319.1**	**11.52-21.44**
Class II Mirror CMS Replacement	Pedestrians	0.14-0.36	1.0-2.8	4.0-10.7	0.53-1.42
	Cyclists	0.18-0.49	2.6-7.1	21.1-56.1	1.22-3.26
	PTWs	0.13-0.35	0.7-2.0	7.2-19.3	0.51-1.37
	Totals	**0.45-1.20**	**4.4-11.8**	**32.3-86.1**	**2.26-6.04**
Class IV Mirrors	Pedestrians	0	0	0.5-0.9	0.008-0.014
	Cyclists	0	4.1-6.7	35.4-58.1	1.41-2.32
	PTWs	0	1.0-1.6	11.5-18.8	0.39-0.64
	Totals	**0**	**5.1-8.3**	**47.4-77.8**	**1.81-2.97**
Class IV Camera Monitor System	Pedestrians	0	0	0.5-0.8	0.008-0.013
	Cyclists	0	3.8-6.3	33.3-54.8	1.33-2.18
	PTWs	0	0.9-1.5	10.6-17.5	0.36-0.59
	Totals	**0**	**4.8-7.8**	**44.4-73.0**	**1.70-2.79**
Class V (Blind Spot) Mirrors	Pedestrians	3.73-6.13	28.5-46.9	99.3-163.1	14.41-23.67
	Cyclists	0	4.8-7.8	37.6-61.8	1.59-2.61
	PTWs	0	0.4-0.6	9.9-16.3	0.24-0.40
	Totals	**3.73-6.13**	**33.7-55.3**	**146.8-241.2**	**16.24-26.67**
	Pedestrians	3.47-5.70	26.5-43.6	92.3-151.6	13.37-21.97
	Cyclists	0	4.5-7.4	35.4-58.2	1.49-2.45

Safety Measure Solution	Casualty Type	Number of Incidents (n)			Total Value (NPV) of Incidents (£M)
		Fatal Casualties	Serious Casualties	Slight Casualties	
Class V (Blind Spot) Camera Monitor System	PTWs	0	0.4-0.6	9.2-15.1	0.22-0.37
	Totals	**3.47-5.70**	**31.4-51.5**	**136.9-225.0**	**15.09-24.79**
Reversing Camera Monitor System	Pedestrians	0.24-0.39	0	1.0-1.6	0.46-0.75
	Cyclists	0	0	0.3-0.5	0.005-0.008
	PTWs	0	0	0.5-0.7	0.007-0.012
	Totals	**0.24-0.39**	**0**	**1.7-2.8**	**0.47-0.77**
360° Camera Monitor System	Pedestrians	5.40-11.02	26.4-53.9	111.7-227.9	17.2-35.12
	Cyclists	0.73-1.50	9.8-19.9	81.6-166.5	4.68-9.54
	PTWs	0.35-0.71	2.3-4.6	27.3-55.8	1.55-3.17
	Totals	**6.48-13.23**	**38.5-78.5**	**220.7-450.2**	**23.44-47.83**
Nearside VRU Information System	Pedestrians	3.16-3.29	19.7-19.7	70.9-70.9	11.03-11.28
	Cyclists	1.14-1.27	9.1-9.4	75.0-77.3	5.17-5.51
	PTWs	0.40-0.45	1.0-1.0	9.9-10.2	1.10-1.20
	Totals	**4.70-5.01**	**29.8-30.1**	**155.8-158.4**	**17.31-17.98**
Forward VRU Information System	Pedestrians	7.51-7.82	25.2-25.2	121.4-121.4	20.99-21.57
	Cyclists	0.57-0.64	1.4-1.4	16.5-17.0	1.60-1.74
	PTWs	0	0.2-0.3	6.2-6.4	0.15-0.15
	Totals	**8.08-8.46**	**26.9-26.9**	**144.0-144.8**	**22.74-23.46**

7.5 Cost implications

The costs of implementing the direct and indirect vision performance requirements as part of the bus safety standard can be divided into five key cost categories based on:

1) Differences in technology development, manufacturing and certification costs
2) Differences in implementation and installation costs
3) Differences in ongoing operational costs
4) Differences in insurance claims costs
5) Differences in environmental and infrastructure costs

A number of approaches were adopted to estimate baseline industry-wide cost values both for each safety measure solution and for each of key cost category. Although greater detail regarding baseline costs may be found in the stakeholder consultation report, the following paragraphs summarise the cost values utilised by this project for each safety measure solution and key cost category.

To estimate the expected changes in costs associated with technology development, manufacturing and certification for each safety measure solution, initial baseline cost data was abstracted from four key resources:

- Initial baseline technology costs for retrofit CMS systems (dual camera) were abstracted from Commercial Motors (2017);
- Costs for a retrofit 360° CMS were taken from an aftermarket solution produced by Brigade (2017); and
- The costs for aftermarket ultrasonic sensor systems, abstracted from Commercial Motors (2017) and HGV Direct Parts (2017), were proposed to estimate costs for both the nearside and forward VRU information systems.

No objective data was found from the literature to guide the costs of replacing the driver assault screen. The data collected was then presented to, reviewed and updated by key bus industry stakeholders through the Stakeholder Consultation process to provide bus industry agreed ranges for the estimated changes in both retrofit and new build technology costs for each safety measure solution. These agreed costs were used to estimate the net present value (NPV) change in technology costs per fitted bus and the total costs for the whole fleet for each safety measure solution for the 2019-2031 analysis period.

When considering the expected changes in implementation and installation costs associated with the direct and indirect vision safety measure solutions, the estimates of baseline costs were principally determined based on the feedback from the Stakeholder Consultation. Bus manufacturers, suppliers and operators were requested to provide an estimate of additional one-off costs associated with implementing and installing each safety measure solution. This resulted in cost estimates primarily calculated from the combination of the times taken to install and train the drivers to use the systems with the cost per hour of each of these tasks. It was assumed that new build solutions would not accrue any additional costs relating to installation, resulting in a zero change in costs associated with these solutions. Additional costs relating to driver training were assumed to affect the 360° CMS and forward/nearside VRU information systems only, with 2-4 person-hours required for this additional training. Training relating to the remaining safety measures was assumed to occur as part of standard driver training. Finally, the time (and therefore costs) to install the retrofit solution systems was agreed between operators and suppliers through the Stakeholder Consultation for each safety measure. These costs were then used to estimate the net present value (NPV) change in implementation costs per fitted bus and the total costs for the whole fleet for each safety measure solution for the 2019-2031 analysis period.

Changes in operational costs were estimated based on operator and supplier feedback from the Stakeholder Consultation. This primarily focussed on the estimated changes in the costs associated with maintenance of the safety measure solutions. Mirror based solutions were assumed to have operational costs associated with replacing these additional mirrors when damage by a mirror strike. CMS and VRU information system-based solutions were assumed to have a change in operational costs associated with an increase in the maintenance costs associated with the system. All other solutions were assumed to be cost neutral due to no required changes in operational practices. These costs were then used to estimate the net present value (NPV) change in operational costs per fitted bus and total costs for the whole fleet for the 2019-2031 analysis period.

The annual changes in incidents may be used to estimate the changes in insurance claims costs that may be expected by regulating the performance of buses for each safety measure solution.

Table 30 and Table 31 summarise the cost data relating to new build and retrofit implementation of the DIV safety measure solutions.

Cost differentials resulting from environmental or infrastructure costs were not considered within the scope of this safety measure. Please see the associated stakeholder consultation report for further information on the relevant costs associated with the implementation of the direct and indirect vision safety measure solutions.

Table 30: Estimated changes in costs per bus (NPV) and total fleet costs (NPV) over the 12-year analysis period (2019-2031) for the new build direct and indirect vision [DIV] safety measure solutions (cost reductions are shown in (parentheses))

Safety Measure Solution	Cost Description	Cost (NPV) per bus (£)	Total Cost (NPV) (£M)
Minimum DVS Performance Requirements	Change in Technology Costs	0	0
	Change in Implementation Costs	0	0
	Change in Operational Costs	0	0
	Change in Insurance Claims Costs	0	0
	Totals	**0**	**0**
Driver Assault Screen Design Requirements	Change in Technology Costs	344-482	4.75-6.65
	Change in Implementation Costs	0	0
	Change in Operational Costs	0	0
	Change in Insurance Claims Costs	(2)-(1)	(0.03)-(0.01)
	Totals	**342-481**	**4.72-6.63**
Minimum IVS Performance Requirements	Change in Technology Costs	51-75	0.48-0.70
	Change in Implementation Costs	0	0
	Change in Operational Costs	0	0
	Change in Insurance Claims Costs	(35)-(6)	(0.33)-(0.05)
	Totals	**16-69**	**0.15-0.65**
Enhanced IVS Performance Requirements	Change in Technology Costs	243-1026	1.94-8.21
	Change in Implementation Costs	0	0
	Change in Operational Costs	265-741	2.12-5.93
	Change in Insurance Claims Costs	(165)-(70)	(1.32)-(0.56)
	Totals	**343-1697**	**2.74-13.58**
Class II Mirror CMS Replacement	Change in Technology Costs	449-897	4.13-8.26
	Change in Implementation Costs	0	0
	Change in Operational Costs	291-815	2.68-7.49
	Change in Insurance Claims Costs	(44)-(13)	(0.41)-(0.12)
	Totals	**695-1699**	**6.40-15.63**
Class IV Mirrors	Change in Technology Costs	52-75	0.52-0.75
	Change in Implementation Costs	0	0
	Change in Operational Costs	110-132	1.10-1.32
	Change in Insurance Claims Costs	(37)-(18)	(0.37)-(0.18)
	Totals	**125-190**	**1.25-1.90**
Class IV Camera Monitor System	Change in Technology Costs	449-897	4.13-8.26
	Change in Implementation Costs	0	0
	Change in Operational Costs	291-815	2.68-7.49
	Change in Insurance Claims Costs	(33)-(16)	(0.30)-(0.15)
	Totals	**707-1696**	**6.50-15.60**
Class V (Blind Spot) Mirrors	Change in Technology Costs	52-75	0.52-0.75
	Change in Implementation Costs	0	0
	Change in Operational Costs	110-132	1.10-1.32
	Change in Insurance Claims Costs	(172)-(85)	(1.72)-(0.85)
	Totals	**(10)-122**	**(0.10)-1.22**
Class V (Blind Spot) Camera Monitor System	Change in Technology Costs	449-897	4.13-8.26
	Change in Implementation Costs	0	0
	Change in Operational Costs	291-815	2.68-7.49
	Change in Insurance Claims Costs	(152)-(75)	(1.40)-(0.69)
	Totals	**588-1637**	**5.41-15.06**
Reversing Camera Monitor System	Change in Technology Costs	26-31	0.28-0.33
	Change in Implementation Costs	0	0
	Change in Operational Costs	89-249	0.95-2.66

Safety Measure Solution	Cost Description	Cost (NPV) per bus (£)	Total Cost (NPV) (£M)
	Change in Insurance Claims Costs	(1)-0	(0.006)-(0.003)
	Totals	**114-280**	**1.22-2.99**
360° Camera Monitor System	Change in Technology Costs	1028-1355	9.46-12.47
	Change in Implementation Costs	104-311	0.95-2.86
	Change in Operational Costs	291-815	2.68-7.49
	Change in Insurance Claims Costs	(278)-(109)	(2.56)-(1.00)
	Totals	**1145-2372**	**10.54-21.83**
Nearside VRU Information System	Change in Technology Costs	896-1353	7.17-10.82
	Change in Implementation Costs	104-311	0.83-2.49
	Change in Operational Costs	265-741	2.12-5.93
	Change in Insurance Claims Costs	(94)-(74)	(0.75)-(0.59)
	Totals	**1170-2331**	**9.36-18.65**
Forward VRU Information System	Change in Technology Costs	373-746	2.99-5.97
	Change in Implementation Costs	311-104	0.83-2.49
	Change in Operational Costs	265-741	2.12-5.93
	Change in Insurance Claims Costs	(89)-(71)	(0.71)-(0.57)
	Totals	**652-1727**	**5.22-13.82**

Table 31: Estimated changes in costs per bus (NPV) and total fleet costs (NPV) over the 12-year analysis period (2019-2031) for the retrofit direct and indirect vision [DIV] safety measure solutions (cost reductions are shown in (parentheses))

Safety Measure Solution	Cost Description	Cost (NPV) per bus (£)	Total Cost (NPV) (£M)
Minimum DVS Performance Requirements	Change in Technology Costs	N/A	N/A
	Change in Implementation Costs	N/A	N/A
	Change in Operational Costs	N/A	N/A
	Change in Insurance Claims Costs	N/A	N/A
	Totals	**N/A**	**N/A**
Driver Assault Screen Design Requirements	Change in Technology Costs	N/A	N/A
	Change in Implementation Costs	N/A	N/A
	Change in Operational Costs	N/A	N/A
	Change in Insurance Claims Costs	N/A	N/A
	Totals	**N/A**	**N/A**
Minimum IVS Performance Requirements	Change in Technology Costs	67-95	0.72-1.03
	Change in Implementation Costs	48-57	0.52-0.62
	Change in Operational Costs	0	0
	Change in Insurance Claims Costs	(73)-(12)	(0.79)-(0.13)
	Totals	**41-140**	**0.45-1.53**
Enhanced IVS Performance Requirements	Change in Technology Costs	301-1319	3.28-14.34
	Change in Implementation Costs	377-1366	4.10-14.85
	Change in Operational Costs	404-1131	4.39-12.30
	Change in Insurance Claims Costs	(303)-(130)	(3.29)-(1.41)
	Totals	**779-3687**	**8.47-40.09**
Class II Mirror CMS Replacement	Change in Technology Costs	569-1139	6.19-12.38
	Change in Implementation Costs	380-911	4.13-9.91
	Change in Operational Costs	494-1383	5.37-15.03
	Change in Insurance Claims Costs	(92)-(28)	(1.00)-(0.30)
	Totals	**1351-3405**	**14.69-37.02**
Class IV Mirrors	Change in Technology Costs	67-95	0.73-1.04

Safety Measure Solution	Cost Description	Cost (NPV) per bus (£)	Total Cost (NPV) (£M)
	Change in Implementation Costs	48-57	0.52-0.62
	Change in Operational Costs	189-226	2.05-2.46
	Change in Insurance Claims Costs	(74)-(36)	(0.80)-(0.39)
	Totals	**229-343**	**2.49-3.73**
Class IV Camera Monitor System	Change in Technology Costs	569-1139	6.19-12.38
	Change in Implementation Costs	380-911	4.13-9.91
	Change in Operational Costs	494-1383	5.37-15.03
	Change in Insurance Claims Costs	(67)-(33)	(0.73)-(0.35)
	Totals	**1375-3400**	**14.96-36.97**
Class V (Blind Spot) Mirrors	Change in Technology Costs	67-95	0.73-1.04
	Change in Implementation Costs	48-57	0.52-0.62
	Change in Operational Costs	189-226	2.05-2.46
	Change in Insurance Claims Costs	(364)-(181)	(3.96)-(1.96)
	Totals	**(61)-198**	**(0.67)-2.16**
Class V (Blind Spot) Camera Monitor System	Change in Technology Costs	569-1139	6.19-12.38
	Change in Implementation Costs	380-911	4.13-9.91
	Change in Operational Costs	494-1383	5.37-15.03
	Change in Insurance Claims Costs	(328)-(163)	(3.57)-(1.77)
	Totals	**1114-3270**	**12.12-35.56**
Reversing Camera Monitor System	Change in Technology Costs	62-76	0.85-1.04
	Change in Implementation Costs	69-165	0.95-2.28
	Change in Operational Costs	231-646	3.19-8.93
	Change in Insurance Claims Costs	(2)-(1)	(0.03)-(0.01)
	Totals	**359-885**	**4.96-12.24**
360° Camera Monitor System	Change in Technology Costs	1326-1705	14.42-18.54
	Change in Implementation Costs	484-1255	5.26-13.32
	Change in Operational Costs	472-1321	5.13-14.36
	Change in Insurance Claims Costs	(556)-(220)	(6.04)-(2.39)
	Totals	**1726-4030**	**18.76-43.82**
Nearside VRU Information System	Change in Technology Costs	1133-1700	12.32-18.48
	Change in Implementation Costs	294-768	3.19-8.35
	Change in Operational Costs	434-1215	4.72-13.21
	Change in Insurance Claims Costs	(196)-(156)	(2.13)-(1.69)
	Totals	**1665-3527**	**18.10-38.35**
Forward VRU Information System	Change in Technology Costs	472-944	5.13-10.27
	Change in Implementation Costs	199-541	2.17-5.88
	Change in Operational Costs	434-1215	4.72-13.21
	Change in Insurance Claims Costs	(188)-(150)	(2.05)-(1.64)
	Totals	**917-2550**	**9.97-27.73**

7.6 Benefit-cost analysis outcomes

Table 32 provides estimates for the break-even costs, discounted payback period and benefit-cost ratios associated with specifying the performances of both the new build and retrofit buses for each direct and indirect vision safety measure solution. Positive benefit-cost ratios are highlighted in **green**, marginal benefit-cost ratios in **orange** and poor benefit-cost ratios in **red**. Where the total fleet costs (NPV) were calculated to reduce (i.e. changes in insurance claims costs forecasted to be larger than all other costs combined), benefit-cost ratios were classified as **RoI** to identify safety measures likely to provide operators with a return on their investment by 2031.

Table 32: Estimated 12-year analysis period (2019-2031) break-even costs per vehicle (NPV), discounted payback periods and benefit-cost ratios (NPV) for the new build and retrofit direct and indirect vision [DIV] safety measure solutions

Safety Measure Solution	Scenario Type	Break-Even Costs (NPV) (£)	Discounted Payback Period	Benefit-Cost (NPV) Ratio
Minimum DVS Performance Requirements	New Build	Cost Neutral	Cost Neutral	Cost Neutral
	Retrofit	N/A	N/A	N/A
Driver Assault Screen Design Requirements	New Build	53-75	2031+	0.11-0.22
	Retrofit	N/A	N/A	N/A
Minimum IVS Performance Requirements	New Build	53-262	2021-2031+	0.77-16.06
	Retrofit	87-430	2023-2031+	0.62-10.48
Enhanced IVS Performance Requirements	New Build	715-1331	2021-2031+	0.42-3.88
	Retrofit	1059-1972	2026-2031+	0.29-2.53
Class II Mirror CMS Replacement	New Build	128-340	2031+	0.08-0.49
	Retrofit	208-555	2031+	0.06-0.41
Class IV Mirrors	New Build	103-170	2027-2031+	0.55-1.36
	Retrofit	167-274	2029-2031+	0.49-1.19
Class IV Camera Monitor System	New Build	97-159	2031+	0.06-0.22
	Retrofit	156-257	2031+	0.05-0.19
Class V (Blind Spot) Mirrors	New Build	900-1478	2019-2020	7.35-ROI
	Retrofit	1493-2453	2020-2021	7.53-ROI
Class V (Blind Spot) Camera Monitor System	New Build	836-1373	2024-2031+	0.51-2.34
	Retrofit	1388-2280	2026-2031+	0.42-2.05
Reversing Camera Monitor System	New Build	10-16	2031+	0.04-0.14
	Retrofit	34-56	2031+	0.04-0.16
360° Camera Monitor System	New Build	1363-2781	2025-2031	0.57-2.43
	Retrofit	2156-4398	2026-2031	0.53-2.55
Nearside VRU Information System	New Build	998-1037	2031+	0.43-0.89
	Retrofit	1592-1654	2013+	0.45-0.99
Forward VRU Information System	New Build	1301-1342	2024-2031+	0.75-2.06
	Retrofit	2091-2157	2025-2031+	0.82-2.35

From this analysis it is clear that there is only one cost-beneficial solution; this being a requirement for the installation of blind-spot mirrors on buses, with the retrofit scenario being the slightly more cost-effective approach. There are also a total of seven marginally cost-effective solutions, where both new build and retrofit scenarios span a benefit-cost ratio value of 1. It is possible that, due to the cost-saving benefits of clustering multiple safety measures, the cost-effectiveness of these solutions may be further enhanced to provide an increased assurance over their value to the BSS programme. It is clear therefore that Class V blind spot mirrors should be required on all buses as a key recommendation, whilst the cost-effectiveness of the remaining safety measures as part of the wider BSS programme needs to be investigated through the clustered cost-benefit analysis.

8 Summary of conclusions and next steps

8.1 Summary of conclusions

The cost-effectiveness of several proposed solutions was assessed for the Direct and Indirect Vision (DIV) safety measure throughout this project. A range of solutions for improving driver awareness of VRUs passing in close-proximity to the bus were investigated for four key functional safety measure categories; Direct Vision (DIR), Indirect Vision (IND), Internal Obscurations (IOB) and VRU Detection (DET). The technical feasibility, target population, effectiveness, fleet fitment rate and costs associated with implementing each safety measure solution as a requirement of the Bus Vehicle Specification were established. Both the cost-effectiveness and casualty saving benefits of each solution were calculated. These results were then used to confirm the final list of DIV safety measure solutions (described below) recommended for implementation in the Bus Vehicle Specification:

- Blind Spot Mirrors
- Reversing CMS
- Bus Vision Standard
    - Direct Vision
    - Driver Assault Screens
    - Enhanced Indirect Vision
- Blind Spot Information, Warning and Intervention Standard
    - Forward VRU Detection Systems
    - Nearside VRU Detection Systems
- Replacement Camera Monitor Systems (CMS)
    - Replace Class II Mirrors with a Class II CMS
    - Replace Blind Spot Mirrors with Blind Spot CMS

Through the process presented in this report, several proposed solutions were not selected for final inclusion in the Bus Vehicle Specification. Only the blind spot mirror solution was found to have a high certainty of being cost-effective. Therefore, the selection of included safety measure solutions was also based on the value of the expected casualty saving benefits or on a specific need expressed by TfL.

The Bus Vehicle Specification requirements for each recommended safety measure solution are based on the research presented in this report. These have been derived through a combination of analysing the collision landscape specific to the safety measure solution, the most effective specifications to apply to the solution, the cost of applying the specifications to the solution and the current testing and assessment procedures used to establish performance against the proposed specifications. The objectives of the requirements of each proposed solution are described in the following paragraphs.

This research was completed in 2018. The detailed specification, assessment procedures and guidance notes have been incorporated into the Transport for London specification for buses, which is a continuously updated document to keep pace with the latest technological and research developments. This report is not the specification for a bus and should not be used as such. Bus operators, manufacturers, and their supply chain should consult with TfL for the specification.

Blind Spot Mirrors

The blind spots rearward of the driver seat, on both the nearside and offside of the bus, are areas that are not visible to drivers through either direct vision or an indirect vision device. These blind spots were established through innovative research that plotted the space around the bus visible to the driver, thus identifying areas where VRUs can manoeuvre in close-proximity to a bus without a driver being aware of their presence. As a result, it is recommended that the BSS shall specify the immediate retrofit installation of blind spot mirrors across the current TfL bus fleet to remove these critical blind spot zones. Requirements shall be set to ensure visibility of the defined blind spot zone is provided to drivers through an indirect vision device, with blind spot mirrors being the preferred retrofit device because of their lower roll-out costs.

Reversing Camera Monitor Systems (CMS)

Another important blind spot found around the vehicle was found to be the area directly behind the bus. Despite buses rarely performing reversing manoeuvres during normal operational driving, a larger number of reversing manoeuvres are performed in depots and other private property settings. It is therefore recommended that the BSS requires all new buses to install rearward facing reversing CMS to minimise the risks of serious injury caused by reversing buses. These field of vision requirements shall be based on the latest version of the UN Regulations that underpin rearward field of vision requirements.

Bus Vision Standard (BVS)

Improving the direct and indirect vision performance of a bus is important to ensuring drivers are provided with a field of vision to view VRUs manoeuvring in close-proximity to the bus. The BSS provides a standardised test and assessment protocol (the Bus Vision Standard) that may be used to calculate the total volume around the bus visible to the driver through direct vision and indirect vision devices. These protocols may be used to maintain the existing excellent levels of direct vision, improve indirect vision performance and prevent internal obscurations. The DAS has an essential role in driver vision and should be designed to provide security for drivers, and to minimise vision obstructions such as glazing reflections. The cleaning routines and not allowing stickers on DAS are important for all buses, regardless of operational route or special duties.

Through calculating Bus Vision Performance Scores, each bus may be compared to pass/fail criteria that not only ensures a step change in bus vision safety, but also incentivises improvements beyond minimum requirements. It is recommended that the Bus Vision Standard specifies minimum requirements for direct vision from 2021, with this primarily looking to ensure future bus front end designs, when considering internal obscurations, maintain current performance levels. It is also recommended that minimum requirements for indirect vision be required from 2024, leading to a step change in the indirect field of vision provided to the driver.

Blind Spot Information, Warning and Intervention (BSW) Standard

Despite providing the driver with an improved field of vision, the driver may still not be aware of the presence of VRUs in close-proximity to the vehicle. This may be because of drivers already being focused on other driving hazards, the rapid development of hazards involving VRUs and other distractions that may increase driver workload. In these instances, it may be critical to have an alerting system that rapidly detects, and draws the attention of the driver towards, evolving hazards involving a VRU. Detection of VRUs in such scenarios must be highly accurate and minimise false positives, to ensure drivers are not irritated by false signals. The Blind Spot Information, Warning and Intervention (BSW) Standard provides standardised test and assessment protocols that place requirements on both the technical and human-machine interface performance of such systems. It is recommended that the BSS requires the installation of VRU detection systems on new buses from 2024, with a focus on detecting VRUs in front of and towards the nearside of a bus. Based on the safety approach of the bus manufacturer an option should remain open as to whether an information signal, a collision warning signal or motion inhibit system is provided; with minimum requirements for each provided by the BSW Standard.

Replacement Camera Monitor Systems (CMS)

Camera Monitor Systems (CMS) are now entering the automotive market, with these systems typically replacing Class II mirrors with cameras that provide similar fields of view. Images are shown on a monitor that is often mounted inside the vehicle in a similar location as the exterior mirror. These systems have the advantage of removing the exterior mirrors, which removes the risk of mirror strike injuries to pedestrians and other road users, and also by bringing the monitor image(s) closer to the driver than a mirror system would be able to achieve. It is recommended that the BSS requires CMS to be fitted to new buses from 2021, however further research is needed to define exactly how this should be implemented on buses to ensure a suitable cab layout that does not over-burden the driver with information.

8.2 Next steps

Several proposed safety measure solutions require further research to compliment and refine the relevant Bus Vehicle Specifications. The following section therefore provides an overview of the future steps proposed by this project for these key safety measure solutions.

Whilst five bus models were evaluated using the BVS approach, this standard was based on research being performed by Loughborough Design School into HGV direct vision performance on behalf of the TfL Freight team. Since performing this research, significant updates have been made to the protocol, resulting in different testing and assessment methods that would likely change the results achieved by this research (e.g. the use of monocular instead of binocular eyepoints). As this updated protocol is being used to evaluate the direct vision performance of all HGVs in the Greater London fleet, and is currently being assessed at the UNECE level for implementation in future UN Regulations, it seems important to align with these updates and evaluate their impact on the BVS and its minimum requirements. It is therefore recommended that further investigation of the direct and indirect vision performance of buses is performed against an updated BVS. This may take the form of requesting manufacturers submit a single bus model for evaluation, which may then be evaluated to reset the minimum performance requirements for the BVS. This will provide TfL with a broader range of manufacturer designs (all five bus models were sourced from a single manufacturer in this study) to better represent the results and performance criteria that may be expected from future UN Regulations.

No buses were assessed using the BSW Standard, primarily because of the availability of VRU detection devices to test. Such devices were, however, tested on HGVs for the Blind Spot Safety System project (sponsored by the TfL Freight team), that the BSW Standard protocols were heavily based on. It would therefore be recommended that further trial assessments are performed before finalising the technical performance specifications of the BSW Standard. In addition to updating the technical performance specifications, the human-machine interface (HMI) elements of the BSW Standard were primarily based on the requirements of ISO 15006 and ISO 15008. It is recommended that further research be performed to refine these HMI requirements to reflect the best practices in HMI design currently adopted within the bus sector.

Whilst this research establishes the effectiveness of replacing the Class II mirrors with an equivalent Camera Monitor System, it made several assumptions about the human-machine interface (HMI). To therefore maximise the casualty saving benefits of this safety measure solution, it is important to maximise the effectiveness of the HMI of the CMS with the driver. This includes implementing best practices in camera and monitor placement and the minimising of any increases in driver workload beyond an acceptable level. It is recommended therefore that an investigation of the current state-of-the-art is required to supplement current recommendations.

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Appendix A: General cost-benefit analysis approach

The following Appendix summarises the general approach taken to perform the cost-benefit analysis (CBA) for each safety measure and its proposed solutions over the 12-year analysis period (2019-2031). Using the research presented in previous sections, a number of key CBA outcomes can be determined for each safety measure solution. These outcomes include values for the target populations, effectiveness, fleet fitment timeframes, casualty reduction benefits, costs per vehicle, total fleet costs, monetised casualty benefits, break-even costs and benefit-cost ratios associated with each solution. The theory behind calculating these values is covered in the following paragraphs.

The target population represents the total number of casualties and/or incidents that a particular safety measure solution has been designed to prevent or mitigate each year. Target populations may be calculated for each relevant casualty type (pedestrians, cyclists, powered two wheelers, car occupants, HGV/LGV occupants and bus occupants) and collision severity level (fatalities, serious injury, slight injury, major damage-only incident and minor damage-only incident) using a range of sources. These may be either directly calculated using casualty numbers from the STATS19 database or through the combination of top-level STATS19 data with an indication of the proportion of relevant casualties from other sources (Equation 1). Further information on what approach was adopted is provided in the relevant following section.

$$Target\ Population = Total\ No.of\ Casualties \times Proportion\ of\ Relevant\ Casualties$$

(Equation 1)

The effectiveness of a safety measure solution is determined by an estimate of how well the particular solution works for the specific target population. Estimates of effectiveness may be calculated based on the percentage of relevant target population casualties or incidents that could have been prevented, or severity mitigated, should the particular safety measure be implemented. Overall effectiveness values may therefore be calculated through several different approaches, including values taken directly from testing performed as part of the BSS project and from those abstracted from the literature. Overall effectiveness may also be indirectly calculated by combining technology effectiveness values from studies with similar scenarios or target populations with percentage based correction factors, such as driver reaction factors (Equation 2). Further information on the approach adopted is provided in the relevant following section.

$$Overall\ Effectiveness = Technology\ Effectiveness\ \times Driver\ Reaction\ Factor \times \cdots$$

(Equation 2)

Fleet fitment and implementation timescales were determined for each safety measure solution based on a stakeholder consultation with the bus industry. This was used to include the temporal aspects of the penetration of each safety measure solution in to the TfL fleet, which can then be used for better determining the changes in costs and benefits over time. The ‘first-to-market’ timescales were established based on bus manufacturer feedback and represent the earliest point in time that the leading manufacturer will be able to bring the particular solution to market. The timescales for ‘policy implementation’ were proposed by TfL based on bus manufacturer feedback on when series production would be possible for at least three different manufacturers.

Current levels of fleet fitment for each solution were established based on bus operator feedback, whilst the estimated period of time that it would take to fit the entire TfL fleet with the solution was determined for new build buses (12 years), solutions fitted during refurbishment (7 years) and retrofit solutions (timeframes based on supplier feedback). This gave a year-on-year fleet penetration value, based on the proportion of the fleet fitted with the particular solution, for each solution and each year of the analysis period.

Total casualty reduction benefits were then calculated by multiplying the target population and overall effectiveness values together with fleet penetration for each year of the analysis period (Equation 3). To correct for changes in the modal share in London, target population values were adjusted according to the forecasted growth in the number of trips made by each transport mode within London, whilst the bus fleet size was adjusted by the forecasted growth in the population of London (based on TfL forecasts (Transport for London, 2015)). These values were then aggregated to provide the total casualty reduction values associated with each target population and severity level over the total analysis period.

$$Casualty\ Reduction\ = Target\ Population \times Overall\ Effectiveness \times Fleet\ Penetration$$

(Equation 3)

These values were then monetised to provide an estimate of the societal benefits of the casualty reductions to TfL using 2016 average casualty costs calculated by the Department for Transport (DfT) for each relevant severity level (Department for Transport, 2018). For the purposes of this report, fatal casualties were assigned a value of £1,841,315, seriously injured casualties assigned a value of £206,912, slightly injured casualties assigned a value of £15,951 and major damage-only collisions assigned a value of £4,609 based on these DfT estimates, whilst minor damage-only collisions were assigned a value of £1,000 based on a reasonable estimate for such collisions. Net present values (NPV) for the monetised casualty saving benefits for each solution were then calculated for the analysis period. A discounting factor of 3.5% and interest rates that reflect forecasted annual changes in the retail pricing index (RPI), as defined by the WebTAG databook (v1.11) (Department for Transport, 2018), were applied.

When considering the cost based outcomes, both the costs per vehicle and total fleet costs were calculated for each solution. These were based on estimated increases in costs related to the development, certification, implementation and operation of the proposed solution and included operational cost reductions due to a reduction of claims costs associated with the reduction in casualties. The baseline costs per vehicle were adopted from information abstracted from the literature and manufacturer/supplier websites, before aggregating and confirming the estimated cost ranges through stakeholder consultation. Fleet costs were then calculated by multiplying the baseline costs per vehicle and fleet penetration values together for each year of the analysis period (Equation 4).

Claims costs reductions for each year of the analysis period were calculated by combining average insurance claim costs (calculated from operator provided data), with the expected annual changes in incidents for each outcome severity (Equation 4). For the purposes of this report, claims reductions for fatalities was assigned a range of £35,000-45,000, seriously injured casualties assigned a range of £60,000-70,000, slightly injured casualties assigned a range of £6,000-8,000, major damage-only collisions assigned a range of £4,000-5,000 and minor damage-only collisions assigned a range of £1,000-2,000.

Changes in baseline and claims costs were then aggregated to provide the net present value of the total fleet costs over the total analysis period. The net present values of the costs per vehicle were then calculated by dividing the total costs by the total number of fitted vehicles in the fleet. A discounting factor of 3.5% and interest rates that reflect forecasted annual changes in RPI were again applied.

$$Total\ Cost = (Baseline\ Cost \times Fleet\ Penetration) - (Claim\ Cost \times Casualty\ Reduction)$$

(Equation 4)

The break-even costs, discounted payback periods and benefit-cost ratios were calculated for the analysis period by combining values from the net present values for both the costs and monetised benefits. The 12-year analysis period was selected based on a combination of stakeholder and industry expert opinion to ensure the one-off and ongoing costs for each vehicle were combined with the casualty reduction benefits over the estimated operational lifetime of the vehicle. Break-even costs describe the highest tolerable costs per vehicle for the fitment of a safety measure solution to remain cost-effective for society. These were calculated by normalising the monetised casualty reduction benefits by the total number of fitted vehicles in the fleet (Equation 5). This value may be a useful indicator when no cost estimates are available, or there is low confidence in the cost inputs, with higher break-even costs indicating a greater potential for cost-effectiveness.

$$Break\ Even\ Cost = Monetised\ Casualty\ Reduction / Total\ Number\ of\ Buses\ Fitted$$

(Equation 5)

Benefit-cost ratios (BCR) 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 net present value of the total casualty benefits to the net present value of the total costs. As ranges of estimated benefits and costs have been calculated, the greatest possible benefit-cost ratio range was estimated by comparing maximum costs against 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. Should the total costs of implementing the safety measure solution reduce, then the benefit-cost ratio will be shown as a 'Return on Investment' (RoI) to indicate that the safety measure solution is likely to provide operators with a return on their investment within the analysis period.

$$Benefit - Cost\ Ratio = Monetised\ Casualty\ Reduction / Total\ Cost$$

(Equation 6)

Finally, the discounted payback period (DPP) was established based on calculations for the benefit-cost ratio ranges for each year of the analysis period. To establish the DPP range, the year where each boundary of the benefit-cost ratio first exceeded the value of 1 was calculated. This gives a range for the expected period in time where the societal benefits of implementing the safety measure solution would outweigh the costs of doing so. Should any boundary of the DPP be greater than 2031 (i.e. a BCR value boundary of <1 over the analysis period), then the DPP boundary was assigned a date of 2031+.

Appendix B: Background to optical principles terminology

Reflection occurs when an incident ray (approaching light, see point A in Figure 5252) hits a boundary between one medium and another, such as the surface of a material (unless it has transparent or translucent properties in which case it also happens from within), and rebounds away (reflected ray, see point B in Figure 52) (Tattersall, 2008). The proportion of reflected light with respect to the total incident ray is used to gauge the reflectivity of the material. In scenarios where light passes from one medium to another of a different density e.g. air in to water, refraction will occur (see point C and D in Figure 52). This transition causes the light to change speed and direction. The level of change is determined by the density of the medium the light is travelling in to and whether the incident ray hits the medium boundary head on or at an angle. If the ray hits the boundary head on, the light will either speed up or slow down (depending on density) with no change in direction (see point E in Figure 52). If the ray hits the boundary at an angle the light will either bend towards the normal if the medium has a higher density (see point G in Figure 52) and away if it is less dense (see point F in Figure 52).

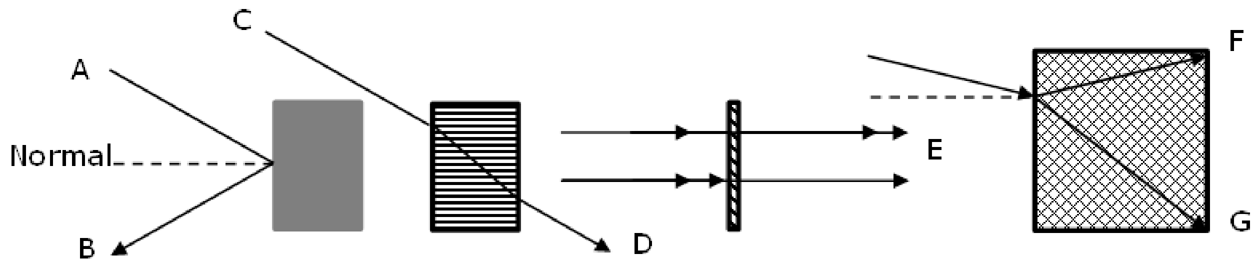

Figure 52: A diagram representing reflection and refraction, adapted from (Tattersall, 2008)

A transparent material allows light to directly transmit through a material without being scattered or absorbed (Tattersall, 2008). This enables an observer looking through a sample of the material to see a clear image of what is on the other side. In context to this project the transmissivity and absorptivity of a material describes how much light passes through the material and is absorbed in relation to the incident ray, respectively. Translucent materials also transmit light, however the light is scattered in a variety of different directions and partly absorbed on its surface, and from within, resulting in a clouded image. An opaque material transmits no light, instead is either reflected, scattered or absorbed.

The angle of incidence (AOI), the angle between an incident ray and the normal (a perpendicular line to the reflecting surface), and angle of refraction (AOR), the angle between a refracted ray and the normal, influence the reflectivity of a material (see Diagram A in Figure 53) (BBC, 2014a). Once an AOR of 90º has been achieved, the AOI is said to be at its critical angle. The critical angle is the maximum angle an incidence ray can strike the surface of a medium for refraction to occur (see Diagram

B in Figure 53). If an incidence ray strikes at a greater angle than this all the light cannot pass through and it will be reflected (see Diagram C in Figure 53).

Within Figure 53, ‘n’ denotes the refractive index of a medium. A refractive index value is a form of measure which indicates how the velocity of light will vary when it passes through a specific material (BBC, 2014a).

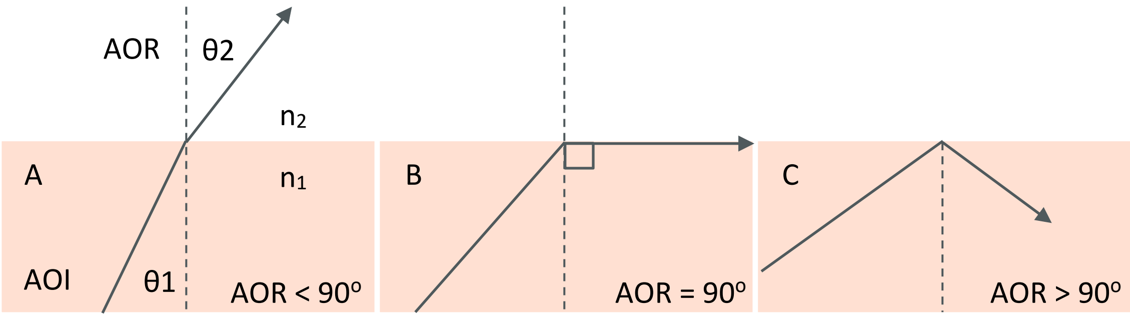

Figure 53: Angles of refraction

The critical angle is different for all materials, see Table 33.

Table 33: A range of refractive index and critical angle values related to buses

Material	Refractive Index	Critical Angle (o)	Source
Generic ideal polycarbonate	1.59	39	(Vrije Universiteit Amsterdam, 2018)
Polycarbonate A	1.586	39.1	Industry
Generic Perspex	1.47	43	(BBC, 2014b)
Generic glass	1.49	42	(BBC, 2014c)

Using the ‘generic ideal’ polycarbonate (see Table 33) as an example, Figure 54 demonstrates the rapid increase in reflected light as the angle of incidence reaches an angle of 90°.

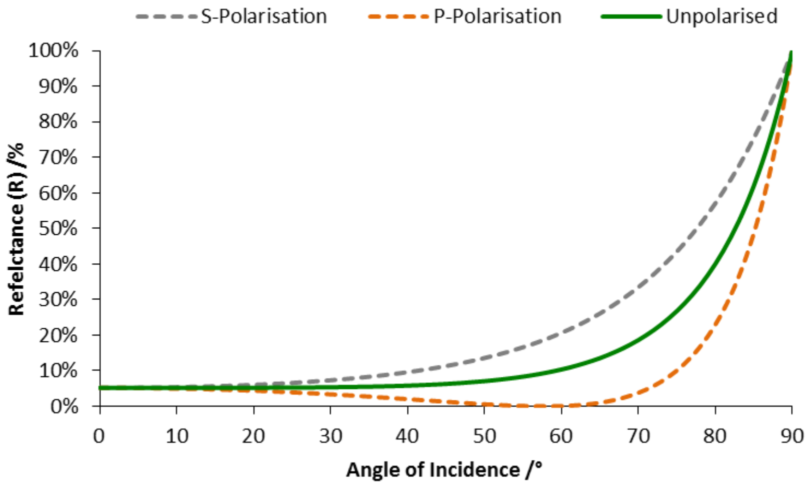

Figure 54: Reflectance of Ideal Polycarbonate

The three lines in Figure 54 and Figure 55 refer to the different orientations light can travel. Light can either be polarised or unpolarised. Polarised light oscillates in a single plane. There are two main types; Primary (P) and Secondary (S) waves. These travel in a longitudinal and transverse direction respectively. Unpolarised light is random.

The reflectance coefficients for P, S and unpolarised (Effective (Eff)) polarisation can be calculated using the following equations (see Equation 7):

$$S - polarisation = \left(\frac{\left(n1 \times COS(\theta)\right) - \mathrm{n2} \times \sqrt{1 - (\frac{n1}{n2} \times SIN(\theta))^2}}{\left(n1 \times COS(\theta)\right) + n2 \times \sqrt{1 - (\frac{n1}{n2} \times SIN(\theta))^2}} \right)^2$$

$$P - polarisation = \left(\frac{n1 \times \sqrt{1 - (\frac{n1}{n2} \times SIN(\theta))^2 - n2 \times COS(\theta)}}{n1 \times \sqrt{1 - (\frac{n1}{n2} \times SIN(\theta))^2 + n2 \times COS(\theta)}} \right)^2$$

$$Eff - polarisation = \frac{\left(S_{reflectance\ coefficient}X + P_{reflectance\ coefficient}X\right)}{2}$$

Equation 7: Reflectance coefficients

By subtracting the reflectance coefficient values from one, transmittance coefficients can be calculated as shown in Equation 8.

$$S - polarisation = 1 - S_{\text{reflectance coefficient}}\,X$$

$$P - polarisation = 1 - P_{\text{reflectance coefficient}}\,X$$

$$Eff - polarisation = 1 - Eff_{\text{reflectance coefficient}}\,X$$

Equation 8: Transmittance coefficients

The percentage transparency of the Driver Assault Screen is introduced to create results which are more representative of real world conditions.

$$S - polarisation = \frac{S_{\text{Transmittance coefficient}} X}{(S_{\text{transmittance coefficient}} X \times \% \, Transparency \, of \, DAS)}$$

$$P - polarisation = \frac{S_{\text{Transmittance coefficient}} X}{(P_{\text{transmittance coefficient}} X \times \% \, Transparency \, of \, DAS)}$$

$$Eff - polarisation = \frac{S_{\text{Transmittance coefficient}} X}{(Eff_{\text{transmittance coefficient}} X \times \% \, Transparency \, of \, DAS)}$$

Equation 9: Normalising transmittance coefficients

The transmittance of DAS Polycarbonate with 87% transmittance at an AOI of 0° can be seen in Figure 55.

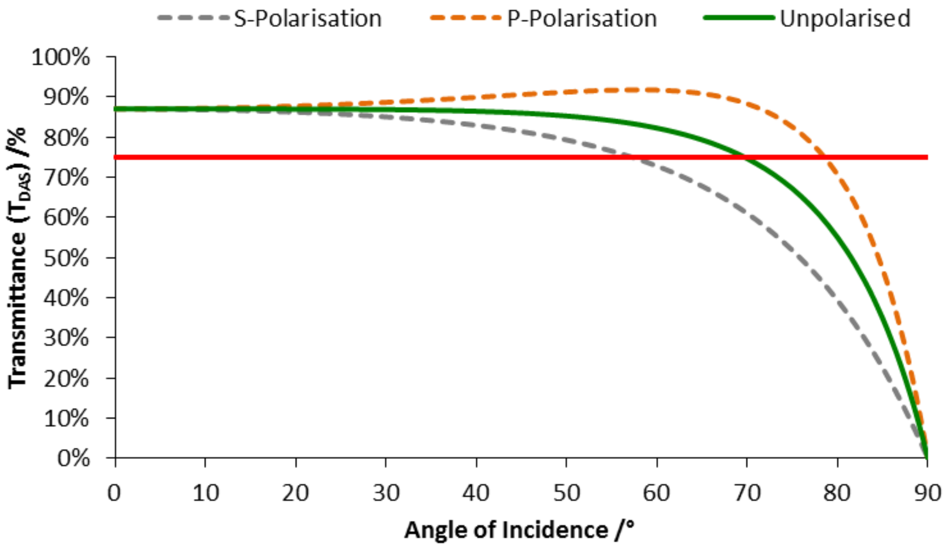

Figure 55: Transmittance of DAS Polycarbonate

Figure 55 highlights at an angle of incidence greater than, approximately, 56° the S-polarisation will start to reduce the transmissive properties of this example Driver assault screen below the 74% minimum threshold. This value increases to 70° and 78° for unpolarised and P-polarisation respectively.

The Transport for London Bus Safety Standard: Direct Vision, Indirect Vision and Detection of Vulnerable Road Users

The Bus Safety Standard (BSS) is focussed on vehicle design and safety system performance and their contribution to the Mayor of London's Transport Strategy. This sets a target to achieve zero road collision deaths involving buses in London by 2030.

All TfL buses conform to regulatory requirements. TfL already uses a more demanding specification when contracting services and this requires higher standards in areas including environmental and noise emissions, accessibility, construction, operational requirements, and more. Many safety aspects are covered in the specification such as fire suppression systems, door and fittings safety, handrails, daytime running lights, and others. However, the new BSS goes further with a range of additional requirements, developed by TRL and their partners and peer-reviewed by independent safety experts.

Good direct and indirect vision alone will not eliminate all casualties in manoeuvring collisions; the driver must still be looking in the right direction at the right time. Systems that give the driver additional information about the hazards around the bus, or warn of an imminent collision, still have an important role to play. How this information is communicated to the driver is critical to their success and a draft standard accounting for different functionalities, the avoidance of false alarms, and the appropriateness of the human machine interface (HMI) has been developed.

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