
THE FUTURE OF TRANSPORT

# PUBLISHED PROJECT REPORT PPR997

# The Transport for London Bus Safety Standard: Vulnerable Road User (VRU) Frontal Crashworthiness

## Evaluation of Safety Measure

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## Report details

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| | | | | |

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# 1 Executive Summary

## 1.1 Bus Safety Standard (BSS)

The Mayor of London's Transport Strategy sets out a commitment to vision zero: no deaths or serious injuries from any collisions on the roads of the capital by 2041, and no fatalities involving a London bus by 2030. The BSS is focussed on the contribution that vehicle safety features can make towards these challenging targets.

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.

## 1.2 Vulnerable Road User (VRU) Frontal Crashworthiness

This safety measure can be described as Partner Protection, or reducing the severity of injuries for road users outside the bus in a collision. More specifically, it concerns the protection of VRUs if a collision with the front of a bus is unavoidable. The aim is to provide better protection and lessen the injury severity. This can include changes to the geometric front end design of the bus, impact energy performance assessment, and runover prevention systems. Also included is the impact performance of wing mirrors and their potential replacement with camera monitor systems (CMS).

### *1.2.1 Impact Protection*

When a collision between the bus and a pedestrian occurs, there is often an impact between the bus and the pedestrian's head. It is possible to reduce the accelerations experienced by the head through the use of energy absorbing materials, avoiding hard points under the front panels in the design stage, or even by altering the front profile of the bus. The BSS sets minimum head impact performance requirements to ensure that the accelerations experienced by the head do not exceed specified injury criteria.

The windscreen wipers can have an effect on pedestrian injuries, should a bus-to-pedestrian collision occur. The wiper mount points are hard and can potentially cause injury. Two potential solutions exist, depending on the bus styling and wiper sweep. First is moving the mount points up to the top of the screen and out of likely impact range. If this is not feasible, a second option is for manufacturers to provide evidence that a protective or energy absorbing covering for bottom-mounted wipers has been fitted and is effective.

### *1.2.2 Bus Front End Design*

Changes to the front end design, or shape of the bus front, can help to deflect the pedestrian out of the path or to scoop them up and along, instead of pushing them down onto the ground. Shape changes for the bus front have been investigated in innovative research using computer simulations. As a result, the BSS will require rounded corners at the front of the bus, combined with a slightly sloped front. These combine to create design envelope requirements to deflect VRUs laterally and upwards away from the bus to reduce injury and run-over risk.

Some of TfL's bus fleet already has these features, and this set of minimum requirements will be adopted in the BSS for new-build buses. Future research to generate more optimised requirements will consider different speeds, different material properties, and cyclists.

### *1.2.3 Run-Over Protection*

Pedestrians are at the greatest risk of fatality if they are run over after an impact. TfL is keen to see innovative designs from bus manufacturers that will help to prevent run-overs. This might include a mechanical or airbag device located under the bus that is only dropped down on contact with a pedestrian. Bombardier has developed the BodyGuard™ system for trams. Run-over protection solutions need development on buses so cannot yet be incorporated into the BSS, but TfL calls for innovation in this area.

### *1.2.4 Mirror Strikes*

Camera Monitor Systems (CMS) are now entering the market for buses, with these systems replacing the wing mirrors with cameras that provide the same view. Images are shown on a monitor that is mounted inside the bus in a similar place to the wing mirror, e.g. on the A-pillar. These systems have the advantage of removing the wing mirrors, which will remove the risk of mirror strike injuries to pedestrians and other road users. The BSS will require that CMS are fitted, but some further research is needed to define exactly how these should be implemented on buses for a suitable cab layout and in a way that does not over-burden the driver with information.

# 2 Introduction to the Bus Safety Standard

## 2.1 The Bus Safety Standard

In 2017 the Mayor of London, Sadiq Khan, set out a 'Vision Zero' approach to road casualties in his draft transport strategy. 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 Bus Safety Standard (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.

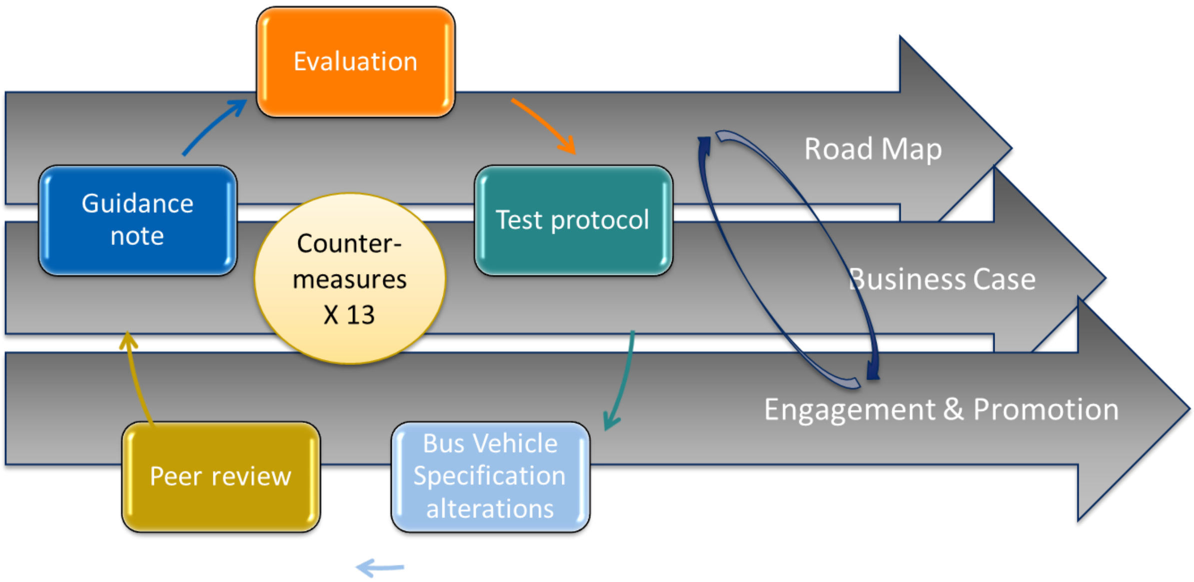



**Figure 1: Summary of the Bus Safety Standard research programme**

The exact methodology of the testing development depended upon each of the measures being developed. For Autonomous Emergency Braking (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 Bus Safety Standard 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 Bus Safety Standard 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.

## 2.2 Bus Safety Measures

The measures selected for consideration in the BSS were wide ranging. 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 assistance 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 assistance, and TfL has already started rolling this out on their fleet. The last two driver assistance 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.

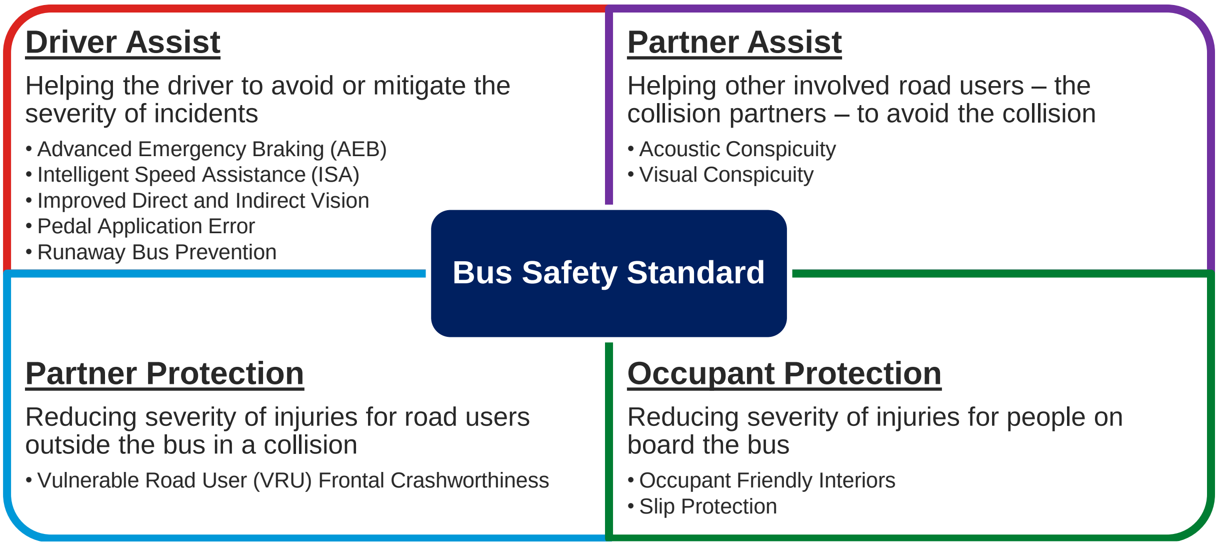



**Figure 2: Bus Safety Measures**

## 2.3 VRU Frontal Crashworthiness

The Vulnerable Road User (VRU) Frontal Crashworthiness (VCW) safety measure will be used to investigate different approaches towards designing the front end of buses to improve the outcomes of collisions with pedestrians and cyclists. The VCW safety measure will be split in to four functional categories; VRU Impact Protection (VIP), VRU Run-over Protection (VRP), enhanced Front End Designs (FED) and Mirror Strikes (MST). The VIP safety measure will look at the approaches for reducing the risks of VRUs being killed or seriously injured by mitigating the impact energies transferred to the VRU during a collision. The VRP safety measure, however, will focus on approaches which prevent the VRU from being run-over by the vehicle during the collision. The FED safety measure will focus on the geometry of the bus front end design envelope to both mitigate the impact energies transferred to the head and reduce the risks of the VRU being run-over by the bus. Finally, the MST safety measure will look at methods that reduce the risks associated with bus mirror strikes.

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

# 3 Defining the Problem

## 3.1 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, they 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. The high-level matrix below in Table 3-1 categorises and prioritises the casualties based on past data for London derived from the GB National collision database.

Table 3-1 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 severely injured in collisions where the bus was coded as going ahead, without negotiating a bend, overtaking, starting or stopping, etc.

## 3.2 Crashworthiness casualty problem

The purpose of this section is to perform a review of target populations associated with the VRU Frontal Crashworthiness (VCW) safety measure. The target population is defined as the total number of fatalities or injured casualties, or damage only collisions, which a particular safety measure intends to either prevent or mitigate. A key factor to be considered when identifying target populations includes characterising the collision scenarios for which the safety measure was originally intended. This includes the identification of causation factors, vehicle manoeuvres, opponent manoeuvres, impact configurations and collision severities in addition to understanding any differences between these characteristics based on vehicle or casualty types. In the context of this project, it is important to ensure the target populations associated with the benefits and disbenefits of implementing a particular safety measure are also identified.

The purpose of the following subsections is to review the collision landscape data relevant to the VCW safety measure and available from national (STATS19) and local (TfL bus collision fatal files) databases, 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 safety measure. A summary of overall target population values, for each secondary safety measure, may then be found in the final summary subsection (Section 3.9).

**Table 3-1: 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%** |

## 3.3 Top-level Collision Landscape

For the VCW safety measure, the TfL BSS requires the consideration of VRU impacts against buses within the Greater London region. Analysis of the STATS19 database has shown that there were 20,404 single vehicle collisions involving buses or coaches in London during the period 2006-2015, resulting in a total of 24,678 casualties. These casualties, broken down by injury severity, are illustrated below in Table 2 for all collision partners and for pedestrians, cyclists and powered two-wheelers (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 that there was a total of 5,799 VRU casualties due to collisions with buses and coaches, which means that VRU casualties make up 23% of all casualties due to collisions with buses and coaches in London (Figure 3). When considering the severity of injury, there was a similar trend with slightly injured VRU casualties. There were 4,600 slightly injured VRU casualties, making up 21% of all slightly injured casualties due to collisions with buses in London. When looking at all seriously injured casualties, however, there was a higher proportion of VRU casualties, with 1,076 seriously injured VRU casualties meaning that 43% of all casualties sustaining serious injuries due to bus collisions in London were VRUs. Finally, the proportion of VRU fatalities compared to all fatalities caused by collisions with buses was observed to be 65%. This highlights that VRUs are more vulnerable to being seriously or fatally injured as a result of a collision with a bus.

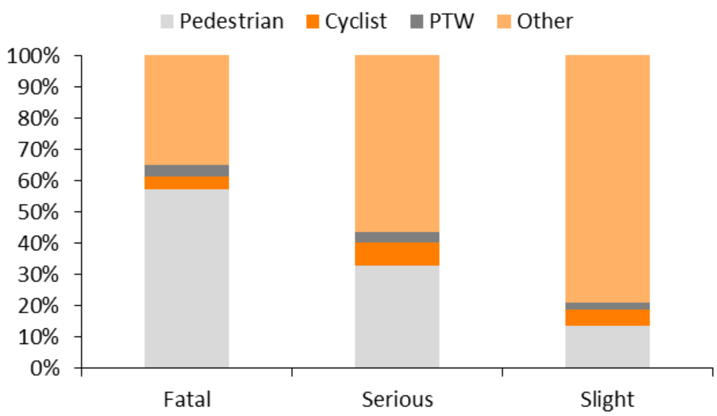



**Figure 3: VRU casualties by injury severity due to collisions where a bus or coach is involved in London between 2006-2015 (data source: STATS19)**

## 3.4 VRU Impact Locations

For the VCW safety measure, it is important to establish the most frequent initial point of impact on a bus for collisions with VRUs. The regions of the bus where the initial point of the impact of the VRU with the bus was recorded are shown below in Table 3. This shows that the front-end of the bus is the most significant region when considering bus collisions with VRU casualties. Analysis of STATS19 showed that there were 2,451 VRU casualties between 2006-2015 where the first point of impact region for the VRU was with the front end of a bus. This means that the initial point of contact for 42% of all VRU casualties is with the front end of a bus. The next highest initial impact region on a bus for VRU casualties is with the nearside of the bus, with 2,204 casualties, which equates to 38% of VRUs impacting the nearside region of a bus during a collision. This is then followed with 10% (588) of VRU casualties initially impacting the offside region of the bus and 3% (201) impacting the rear of the bus.

**Table 3: Number of casualties by initial impact location and injury severity as a result of bus collisions with all VRUs in London between 2006-2015 (data source: STATS19)**

| VRU Casualties | Impact Location | | | | Did Not Impact |
|---|---|---|---|---|---|
| | Front | Nearside | Offside | Rear | |
| **Fatalities** | 76 | 36 | 6 | 2 | 3 |
| **Seriously Injured** | 525 | 376 | 89 | 29 | 56 |
| **Slightly Injured** | 1,850 | 1,792 | 493 | 170 | 295 |
| **Total Casualties** | 2,451 | 2,204 | 588 | 201 | 354 |

When looking at injury severity for VRUs, it can be seen once again that the front-end region of the bus is the most significant region in terms of VRU fatalities. This trend continues for the seriously and slightly injured VRU casualties. There were 76 (62%) VRU fatalities, 525 (49%) seriously injured and 1,850 (40%) slightly injured VRU casualties that initially impacted the front-end of the bus.

The nearside region of the bus is the next most significant region when considering the severity of VRU injuries due to bus collisions. There were 36 VRUs fatalities, initially impacting the nearside of the bus, making up 29% of all VRU fatalities. For seriously and slightly injured VRUs, where the initial point of impact was the nearside of the bus, there were 376 (35%) and 1792 (39%) casualties respectively.

Where the offside region of the bus was the initial point of impact during a collision with a VRU, there were 6 VRU fatalities, which means 5% of all fatalities occurred with the offside of the bus. There were 89 (8%) seriously injured VRU casualties with the first point of impact being the offside region of the bus and 493 (11%) slightly injured VRU casualties.

As would be expected, the rear region of the bus was the least important region in terms of the first point of contact for VRU casualties. There were only 2 fatalities found to impact the rear of the bus, making up 2% of all VRU fatalities. This trend continues with the seriously and slightly injured VRU casualties, with 29 (3%) seriously injured VRU casualties and 170 (4%) slightly injured VRU casualties associated with the rear region of the bus.

### 3.4.1 Pedestrians

When considering pedestrians only, STATS19 data showed that the most significant region in terms of the initial point of contact was the front-end of the bus (Table 4). STATS19 data revealed that 50% (1,976) of all pedestrian casualties occurred due to a collision with the front-end of the bus. There were 69 pedestrian fatalities due to collisions with the front-end region of the bus, making up 64% of all pedestrian fatalities. The statistics also showed that 56% (458) of all seriously injured pedestrian casualties and 48% (1,976) of all slightly injured pedestrian casualties occurred at the front-end of the bus.

The nearside of the bus was the next most significant area when considering pedestrian collisions, with 1,480 pedestrian casualties resulting from collisions with the nearside of the bus, equating to 38% of pedestrian casualties. There were 31 pedestrian fatalities resulting from collisions with the nearside of the bus, making up 29% of all pedestrian fatalities.  There was also 276 (34%) seriously injured and 1173 (39%) slightly injured pedestrian casualties due to the nearside of the bus being the first point of contact during a collision.

**Table 4: Number of casualties by initial impact location and injury severity as a result of bus collisions with pedestrians in London between 2006-2015 (data source: STATS19)**

| Pedestrian Casualties | Impact Location | | | | Did Not Impact |
|---|---|---|---|---|---|
| | Front | Nearside | Offside | Rear | |
| **Fatalities** | 69 | 31 | 4 | 2 | 2 |
| **Seriously Injured** | 458 | 276 | 46 | 3 | 32 |
| **Slightly Injured** | 1,449 | 1,173 | 159 | 30 | 186 |
| **Total Casualties** | 1,976 | 1,480 | 209 | 35 | 220 |

### 3.4.2 Cyclists

When considering the initial point of contact on the bus during collisions with cyclists, the STATS19 database revealed that the nearside of the bus is the most frequently impacted region (Table 5). STATS19 data showed that 48% (608) of all cycle casualties occurred due to collisions with the nearside of the bus. There were 3 fatalities that occurred due to collisions with the nearside of the bus, making up 38% of all cyclist fatalities. A total of 76 seriously injured cyclists collided with the nearside region of the bus, making up 43% of all seriously injured casualties. Finally, for slightly injured casualties, there were 529 casualties due to collisions with the nearside region of the bus, making up 48% of all slightly injured cyclists.

STATS19 data showed that there were 5 fatalities due to collisions with the front-end region of the bus, making up 63% of all cyclist fatalities. For all cyclist casualties, plus seriously and slightly injured cyclist casualties the front-end region of the bus is the second most prominent region. There were 314 cyclist casualties in London due to collisions with the front-end of the bus, making up 25% of all cycle casualties. There were 39 (22%) seriously injured and 270 (25%) slightly injured cycle casualties due to collisions with the front-end region of the bus in London, between 2006 and 2015.

**Table 5: Number of casualties by initial impact location and injury severity as a result of bus collisions with cyclists in London between 2006-2015 (data source: STATS19)**

| Cyclist Casualties | Impact Location | | | | Did Not Impact |
|---|---|---|---|---|---|
| | Front | Nearside | Offside | Rear | |
| Fatalities | 5 | 3 | 0 | 0 | 0 |
| Seriously Injured | 39 | 76 | 26 | 17 | 18 |
| Slightly Injured | 270 | 529 | 150 | 79 | 65 |
| Total Casualties | 314 | 608 | 176 | 96 | 83 |

### *3.4.3 Powered two-wheelers*

Powered two-wheelers (PTWs) are characterised by a greater distribution of collision impact locations when considering collisions with buses in London, with the front end, nearside and offside of the bus all being important to the collision landscape (Table 6). When considering PTW fatalities, each of the front-end, nearside and offside regions of the bus were involved in 2 fatalities each, making up 29% of all PTW fatalities for each region. The bus front end was the most significant region for seriously injured PTWs with 28 (33%) casualties, followed by the nearside of the bus with 24 (29%) casualties and then the offside of the bus with 17 (20%) casualties. Finally, the offside of the bus was the most significant region for slightly injured PTWs with 184 (36%) casualties, followed by the front end of the bus with 131 (26%) casualties and then the nearside of the bus with 90 (18%) casualties.

**Table 6: Number of casualties by initial impact location and injury severity as a result of bus collisions with powered two-wheelers (PTWs) in London between 2006-2015 (data source: STATS19)**

| PTW Casualties | Impact Location | | | | Did Not Impact |
|---|---|---|---|---|---|
| | Front | Nearside | Offside | Rear | |
| Fatalities | 2 | 2 | 2 | 0 | 1 |
| Seriously Injured | 28 | 24 | 17 | 9 | 6 |
| Slightly Injured | 131 | 90 | 184 | 61 | 44 |
| Total Casualties | 161 | 116 | 203 | 70 | 51 |

### *3.4.4 Front end impact location*

Knowles et al. (2012) performed an in-depth review to ascertain in greater detail the exact point of the bus that the VRU impacts during a fatal collision. Analysis of the data shows that 82% (27) of fatal collisions occurred with the front-end of the bus (Table 7). With 45% (15) of fatalities occurring with the front-nearside third of the bus front-end, 28% (9) occurring with the front-centre third of the bus front-end and 9% (3) occurring with the front-offside third. When looking at the nearside region of the bus there was a total of 4 impacts, meaning that 12% of fatal pedestrian collisions can be attributed to the nearside of the bus. When looking at the offside region of the bus there was only 1 impact, meaning that 3% of fatal collisions may be attributed to the offside.

**Table 7: Number of fatalities by Pedestrian impact point with bus or coach (Knowles et al. (2012))**

| Point of Impact* | Number of Pedestrians | Proportion of Pedestrians |
|---|---|---|
| **Front-nearside** | 15 | 45% |
| **Front-centre** | 9 | 28% |
| **Front-offside** | 3 | 9% |
| **Rear-nearside** | 3 | 9% |
| **Nearside** | 1 | 3% |
| **Rear** | 0 | 0% |
| **Offside** | 1 | 3% |
| **Rear-offside** | 0 | 0% |
| **Underneath** | 1 | 3% |
| **Top** | 0 | 0% |

* Nearside: passenger-side of vehicle; Offside: driver-side of the vehicle

Edwards et al. (2018) investigated the impact point distribution around the bus for a total of 20 pedestrian fatalities where the information was available for use. Edwards et al. (2018) divided the width of the bus front-end into five key sections (Figure 4), observing that 60% of all fatalities struck the outermost 500 mm of the front-offside and front-nearside of the bus (30% each), whilst a further 30% of fatalities struck the second 500 mm portion of the front end of the bus in from the nearside of the bus. The final 10% of collisions were found to strike the central 500 mm portion of the bus front end.

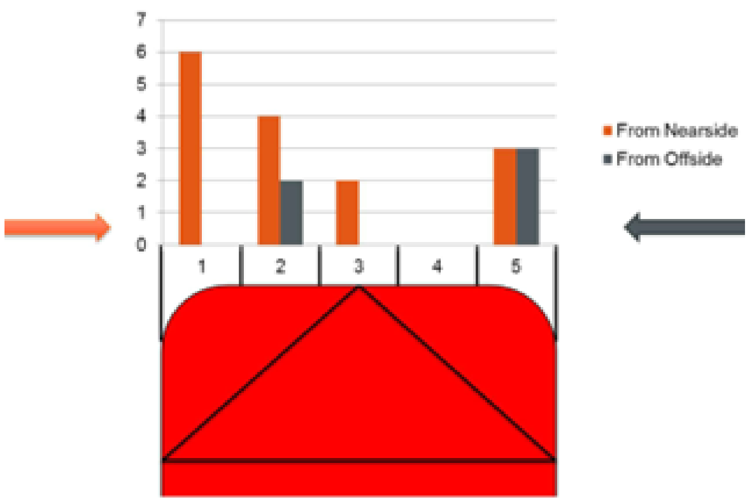



**Figure 4: Distribution of pedestrian impact points across the bus front-end (Edwards *et al.*, 2018)**

From these reviews it is clear that the front-end of the bus is the most critical region to try to improve the crashworthiness of the bus in relation to VRUs and that VRU impacts across the bus front end may be more prevalent towards the edges of the bus. It is therefore recommended that the VCW safety measure focus on front end VRU impacts only.

## 3.5 VRU and Bus Manoeuvres

As it has been determined that the majority of VRU collisions occurred with the front end of the bus, it is now important to understand what manoeuvres were being performed by the VRU and bus in collisions where the VRU struck the bus front end. The following subsections therefore summarise the key manoeuvres of the bus and VRU for each VRU category, where the first point of contact is the bus front end.

### *3.5.1 Pedestrians*

Analysis of the STATS19 database revealed that there were 1,976 pedestrian collisions with the front-end of a bus in London between 2006-2015. When looking at the top three bus manoeuvres that resulted in the bus front end being impacted during a collision between a bus and pedestrian (Table 8), there were 1,255 (64%) pedestrian casualties as a result of the bus going ahead other, 210 (11%) casualties as a result of the bus slowing or stopping and 215 (11%) casualties as a result of the bus moving off. The next two most prominent bus manoeuvres involved 96 (5%) pedestrian casualties during a bus turning right manoeuvre and 84 (4%) casualties during a bus turning left manoeuvre (Table 8). This shows that the majority of collisions (86%) between the front end of a bus and a pedestrian occur whilst the bus is manoeuvring in a straight line.

**Table 8: Number of casualties by key bus manoeuvre and injury severity for pedestrian collisions with the front end of buses in Greater London between 2006-2015 (data source: STATS19)**

| Pedestrian Casualties | Key Bus Manoeuvres | | | | |
|---|---|---|---|---|---|
| | Going Ahead Other | Slowing or Stopping | Moving Off | Turning Left | Turning Right |
| **Fatalities** | 41 | 2 | 9 | 5 | 8 |
| **Seriously Injured** | 334 | 34 | 28 | 15 | 18 |
| **Slightly Injured** | 880 | 174 | 178 | 64 | 70 |
| **Total Casualties** | 1,255 | 210 | 215 | 84 | 96 |

When analysing the manoeuvres of pedestrians involved in collisions with the front end of a bus, it is clear that there are several important pedestrian manoeuvres that characterise the vast majority of collisions (Table 9). Pedestrians were crossing in front of the bus from the nearside of the road for 1,104 (56%) casualties and from the offside of the road in 335 (17%) casualties. There were also 71 (4%) pedestrian casualties crossing in front of the bus from the nearside of the road and 52 (3%) pedestrian casualties crossing in front of the bus from the offside of the road whilst masked by an obstruction. Finally, pedestrians were stationary in the carriageway for 48 (2%) casualties. Importantly, it should also be noted that 343 (17%) of pedestrian casualties were coded with an unknown or other manoeuvre. This shows that the majority of collisions (79%) between the front end of a bus and a pedestrian occur whilst the pedestrian is crossing the road, particularly from the nearside of the bus (59%).

**Table 9: Number of casualties by key pedestrian manoeuvre and injury severity for pedestrian collisions with the front end of buses in Greater London between 2006-2015 (data source: STATS19)**

| Pedestrian Casualties | Key Pedestrian Manoeuvres | | | | |
|---|---|---|---|---|---|
| | Crossing from Nearside | Crossing from Offside | Crossing from Nearside - masked | Crossing from Offside - masked | In Carriageway Stationary |
| **Fatalities** | 34 | 16 | 3 | 0 | 1 |
| **Seriously Injured** | 280 | 67 | 25 | 12 | 11 |
| **Slightly Injured** | 790 | 252 | 43 | 40 | 36 |
| **Total Casualties** | 1,104 | 335 | 71 | 52 | 48 |

### *3.5.2 Cyclists*

Analysis of the STATS19 database revealed that there were 314 cyclist collisions with the front-end of a bus in London between 2006-2015. The leading bus manoeuvre performed during bus front end to cyclist collisions was going ahead other, which resulted in 167 (53%) cyclist casualties (Table 10). This was then followed up by the bus moving off and turning right for 35 (11%) casualties for both manoeuvres, the bus slowing or stopping for 22 (8%) casualties, the bus overtaking the cyclist on the offside for 16 (5%) casualties and the bus turning left for 13 (4%) casualties. This shows that the majority of collisions (76%) between the front end of a bus and a cyclist occur whilst the bus is manoeuvring in a straight line.

**Table 10: Number of casualties by key bus manoeuvre and injury severity for cyclist collisions with the front end of buses in Greater London between 2006-2015 (data source: STATS19)**

| Cyclist Casualties | Key Bus Manoeuvres | | | | | |
|---|---|---|---|---|---|---|
| | Going Ahead Other | Slowing or Stopping | Moving Off | Turning Left | Turning Right | Overtaking on Offside |
| **Fatalities** | 3 | 0 | 0 | 0 | 1 | 0 |
| **Seriously Injured** | 25 | 2 | 2 | 1 | 4 | 2 |
| **Slightly Injured** | 139 | 20 | 33 | 12 | 30 | 14 |
| **Total Casualties** | 167 | 22 | 35 | 13 | 35 | 16 |

When analysing the manoeuvres of cyclists involved in collisions with the front end of a bus, it is clear that there are several important cyclist manoeuvres that characterise the majority of collisions (Table 11). Cyclists were going ahead other in 157 (50%) of collisions, resulting in this being the leading manoeuvre performed during bus front end collisions with cyclists. There were also 32 (10%) cyclist casualties that were turning right, 28 (9%) cyclists that were waiting to go or held up, 20 (6%) cyclists that were slowing or stopping, 17 (5%) cyclists that were moving off and 9 (3%) cyclists that were turning left. This shows that the majority of collisions (71%) between the front end of a bus and a cyclist occur whilst the cyclist is either stationary or manoeuvring in a straight line.

**Table 11: Number of casualties by key cyclist manoeuvre and injury severity for cyclist collisions with the front end of buses in Greater London between 2006-2015 (data source: STATS19)**

| Cyclist Casualties | Key Cyclist Manoeuvres | | | | | |
|---|---|---|---|---|---|---|
| | Going Ahead Other | Slowing or Stopping | Moving Off | Turning Left | Turning Right | Waiting To Go - Held Up |
| **Fatalities** | 1 | 0 | 0 | 0 | 1 | 1 |
| **Seriously Injured** | 22 | 1 | 2 | 2 | 4 | 3 |
| **Slightly Injured** | 134 | 19 | 15 | 7 | 27 | 24 |
| **Total Casualties** | 157 | 20 | 17 | 9 | 32 | 28 |

It is unknown, however, whether cyclists that were travelling in a straight line were crossing the path of the bus or were in the same carriageway as the bus, thus making it difficult to interpret the orientation of the cyclist relative to the bus and their direction of travel. When investigating which side of the cyclist was struck, we may be able to infer what manoeuvre the cyclist performed relative to the bus to characterise the collision. These characteristics and their assumptions are as follows:

- **Head-on collision:** Front of bus to front of cyclist
- **Rear-end collision:** Front of bus to rear of cyclist
- **Crossing from nearside collision:** Front of bus to offside of cyclist
- **Crossing from offside collision:** Front of bus to nearside of cyclist

When considering all cyclist and bus manoeuvres, Table 12 below shows how these collision characteristics vary for each injury severity level. It is clear to conclude that, although the most important collision characteristic is the rear-end collision (i.e. where the bus collides with the cyclist by impacting them from the rear), the other three collision characteristics all also contribute considerably to the collision landscape. Not only do rear-end collisions have the greatest incidence, with 151 (48%) of cyclist casualties, but they also have a greater number of fatalities (60%) and slightly injured (50%) casualties at these injury severity levels than any other collision characteristic. From this it may be concluded that the greatest proportion of collisions between cyclists and the front end of a bus occur due to collisions between buses travelling in a straight line and the rear-end of cyclists that were stationary or manoeuvring in a straight line.

**Table 12: Collision incidence for four key collision characteristics between cyclists and bus front ends (data source: STATS19)**

| Cyclist Casualties | Collision Characteristics | | | |
|---|---|---|---|---|
| | Head-On | Rear-End | Nearside Crossing | Offside Crossing |
| **Fatalities** | 0 | 3 | 1 | 1 |
| **Seriously Injured** | 13 | 13 | 7 | 5 |
| **Slightly Injured** | 46 | 135 | 50 | 38 |
| **Total Casualties** | 59 | 151 | 58 | 44 |

### 3.5.3 *Powered two-wheelers*

Analysis of the STATS19 database revealed that there were 161 powered two-wheeler (PTW) collisions with the front-end of a bus in London between 2006-2015. The leading bus manoeuvre performed during bus front end to PTW collisions was going ahead other, which resulted in 79 (49%) PTW casualties (Table 13). This was then followed up by the bus turning right for 26 (16%) PTW casualties, the bus slowing or stopping for 14 (9%) casualties, the bus moving off for 13 (8%) casualties and the bus turning left for 9 (6%) casualties. This shows that the majority of collisions (66%) between the front end of a bus and PTWs occur whilst the bus is manoeuvring in a straight line.

**Table 13: Number of casualties by key bus manoeuvre and injury severity for powered two-wheeler (PTW) collisions with the front end of buses in Greater London between 2006-2015 (data source: STATS19)**

| PTW Casualties | Key Bus Manoeuvres | | | | |
|---|---|---|---|---|---|
| | Going Ahead Other | Slowing or Stopping | Moving Off | Turning Left | Turning Right |
| **Fatalities** | 1 | 0 | 0 | 0 | 0 |
| **Seriously Injured** | 11 | 2 | 2 | 0 | 6 |
| **Slightly Injured** | 67 | 12 | 11 | 9 | 20 |
| **Total Casualties** | 79 | 14 | 13 | 9 | 26 |

When analysing the manoeuvres of PTWs involved in collisions with the front end of a bus, it is clear that there are several important PTW manoeuvres that characterise the majority of collisions (Table 14). PTWs were going ahead other in 62 (39%) of collisions, resulting in this being the leading manoeuvre performed during bus front end collisions with PTWs. There were also 22 (14%) PTW casualties that were turning right, 20 (12%) PTWs that were waiting to go or held up, 16 (10%) PTWs that were slowing or stopping, 9 (6%) PTWs that were turning left and 7 (4%) PTWs overtaking the bus on the offside. This shows that the majority of collisions (61%) between the front end of a bus and a PTW occur whilst the PTW is either stationary or manoeuvring in a straight line, rather than turning or overtaking the bus.

**Table 14: Number of casualties by key powered two-wheeler (PTW) manoeuvre and injury severity for PTW collisions with the front end of buses in Greater London between 2006-2015 (data source: STATS19)**

| PTW Casualties | Key PTW Manoeuvres | | | | | |
|---|---|---|---|---|---|---|
| | Going Ahead Other | Slowing or Stopping | Turning Left | Turning Right | Overtaking on Offside | Waiting To Go - Held Up |
| **Fatalities** | 2 | 0 | 0 | 0 | 0 | 0 |
| **Seriously Injured** | 14 | 2 | 2 | 4 | 0 | 1 |
| **Slightly Injured** | 46 | 14 | 7 | 18 | 7 | 19 |
| **Total Casualties** | 62 | 16 | 9 | 22 | 7 | 20 |

Again, it is unknown whether PTWs travelling in a straight line were crossing the path of the bus or were in the same carriageway as the bus. When investigating which side of the PTW was struck, we may be able to infer what manoeuvre the PTW performed relative to the bus to characterise the collision. These characteristics and their assumptions are as follows:

- **Head-on collision:** Front of bus to front of PTW
- **Rear-end collision:** Front of bus to rear of PTW
- **Crossing from nearside collision:** Front of bus to offside of PTW
- **Crossing from offside collision:** Front of bus to nearside of PTW

When considering all PTW and bus manoeuvres, Table 15 below shows how these collision characteristics vary for each injury severity level. It is clear to conclude that the important collision characteristics are the head-on and rear-end collisions, which result in 51 (32%) and 59 (37%) PTW casualties respectively. Although rear-end collisions have a greater number of casualties, head-on collisions with a bus resulted in greater severity outcomes including the greatest proportion of fatalities (100%) and seriously injured (55%) casualties. From this it may be concluded that the majority of collisions between PTWs and bus front ends occurred due to collisions between buses travelling in a straight line and colliding with either the rear-end or front-end of PTWs that were stationary or manoeuvring in a straight line.

**Table 15: Collision incidence for four key collision characteristics between powered two-wheelers (PTWs) and bus front ends (data source: STATS19)**

| PTW Casualties | Collision Characteristics | | | |
|---|---|---|---|---|
| | Head-On | Rear-End | Nearside Crossing | Offside Crossing |
| **Fatalities** | 2 | 0 | 0 | 0 |
| **Seriously Injured** | 15 | 5 | 4 | 3 |
| **Slightly Injured** | 34 | 54 | 24 | 18 |
| **Total Casualties** | 51 | 59 | 28 | 21 |

## 3.6 Impact Speeds

With the majority of bus front end to VRU collisions typically occurring with both collision partners manoeuvring in a straight line, it is important to determine the speeds at which each collision partner is moving at the point of impact. This data is, however, not specifically recorded within the STATS19 database, requiring estimates to be derived for each collision partner from the existing literature. The following sections therefore briefly summarise the current range of speeds that each collision partner would travel when involved in a collision.

Edwards et al. (2018) provides information on bus travel speeds during fatal collisions with pedestrians. The sample contained 26 fatal pedestrian collisions where the speed of the bus was known, with bus speeds ranging between 3-50 kph at the point of impact. Figure 5 illustrates the number of fatalities and corresponding bus impact speed.

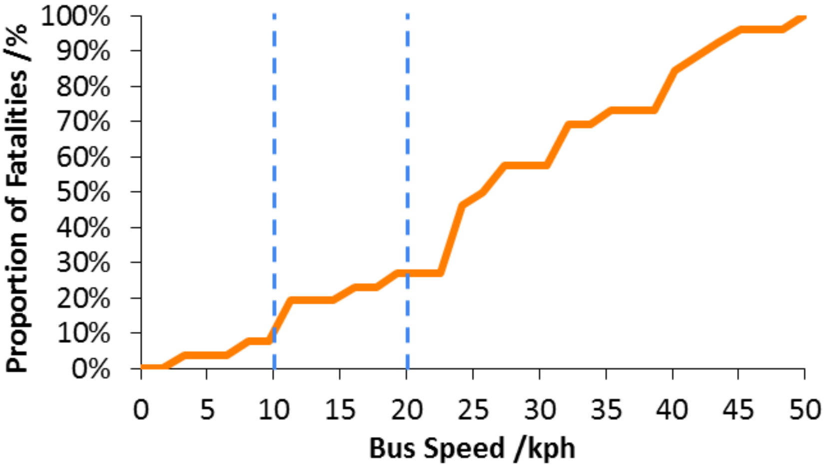



**Figure 5: Bus speed at the point of impact during fatal pedestrian collisions (Edwards *et al.*, 2018)**

Analysis of the of the data shows that approximately 20% of pedestrian fatalities involved in collisions with buses occurred at impacts speeds of <11 kph, 38% of fatalities occurred at impact speeds between 11-30 kph and 42% of fatalities occurred at impact speeds between 30-50 kph. When relating these to the collision landscape statistics reviewed in Section 3.5, it is clear that there are some remarkable parallels between bus manoeuvres and recorded impact speeds. When considering collisions whilst the bus was turning (i.e. speeds of <10 kph) there were 180 (9%) pedestrian collisions (8% in Figure 5). For collisions where the bus was either slowing or stopping or moving off (i.e. speeds of <20 kph), in addition to the turning collisions, there were 605 (31%) pedestrian collisions (27% in Figure 5). Finally, the collisions were where the bus was going ahead other at higher speeds (i.e. speeds of 20-50 kph) contributed to 1,255 (64%) pedestrian collisions (73% in Figure 5).

Current pedestrian walking speeds have been extensively researched, particularly within the field of traffic flow management. Further information on the preferred pedestrian walking speeds, as reported across the literature, may be found in the report by Crabtree *et al*. (2015). Based on this information this project recognises that pedestrians may be crossing the road at speeds between 0- 8 kph when involved in a collision with a bus that is travelling in a straight line.

Cyclist travel speeds at the point of impact may similarly vary between stationary to speeds of up to 43 kph (Boufous *et al.*, 2018) and are highly dependent on the infrastructure and perceived risk. Average travel speeds are found to be approximately 18 kph, but can range between 14-22 kph depending on local variations (Boufous *et al.*, 2018). When considering the speed of the cyclist directly prior to impact, Bourdet *et al*. (2014) found that, across a sample of 24 real-world collisions, estimated cyclist speeds ranged between 0 and 25 kph. Based on this information it could be considered that representative bus vs. cyclist collision characteristics may be caused by rear-end collisions whilst the cyclist is stationary and head-on collisions whilst the cyclist is travelling at 20 kph.

## 3.7 Run-Over Incidents

To assess the frequency and characteristics of VRU run-over incidents, Edwards *et al*. (2018) performed an in-depth analysis of 30 fatalities associated with pedestrians crossing the road and striking the front end of the bus. Of these 30 fatalities, only 10 (33%) were involved in a run-over incident, whilst 19 (63%) were thrown away from the undercarriage of the bus (Table 16). There was no information available on the front end design of the buses involved in these incidents.

**Table 16: Post-impact outcomes for pedestrian impacts with the front end of buses (Edwards *et al.*, 2018)**

| Post Impact Outcome | Number of Fatalities /n | Proportion of Fatalities /% |
|---|---|---|
| **Thrown** | 19 | 63% |
| **Run-over** | 10 | 33% |
| **Other** | 1 | 3% |

On further analysis of the pedestrian run-over collision cases, it was clear that the injured pedestrian body regions could be split into three important categories; head, other regions and unknown. Figure 6 illustrates the number of pedestrian run-over cases associated with each category and illustrates that 40% of run-over casualties sustained head injuries, whilst 40% sustained injuries to other body regions. This shows that all regions of the VRU body are important to consider when assessing the risks of VRU run-over, not just the head.

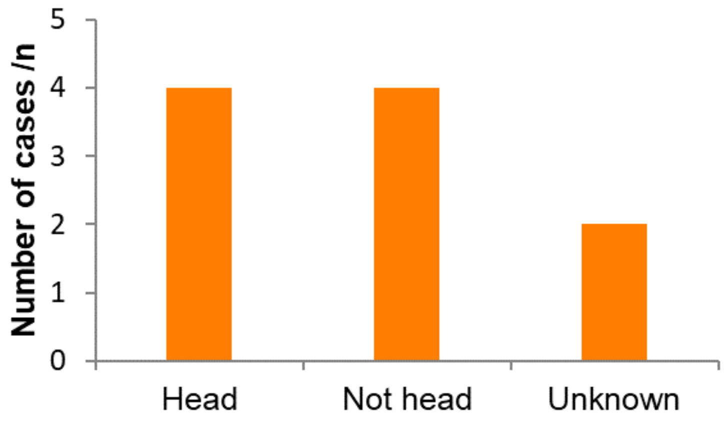



**Figure 6: Pedestrian injured body regions during run-over collisions (Edwards *et al.*, 2018)**

## 3.8 Mirror Strikes

VRU impacts with bus mirrors are also important to consider to better understand the rates and severities of VRU injuries occurring through mirror strikes and for the current levels of damage caused to buses through this mechanism. The following paragraphs summarise the approach taken to evaluate the current mirror strike collision landscape and the outcomes of this assessment.

To perform this analysis, the IRIS dataset currently held by TRL was assessed for the year 2015 in order to evaluate the annual rates and severities of injuries and damage associated with mirror strikes. The "COL_Incidents" field of all 2015 IRIS cases were searched for the term "mirror", before removing duplications and cases that did not involve a mirror strike (e.g. "*the driver looked into the mirror*"). Mirror strike cases were defined as all cases where the bus mirror was recorded as having contacted with VRUs, street furniture, third-party vehicles and other/unknown objects. Where mirrors became detached, this was recorded alongside any secondary objects that the mirror was recorded as having struck. Finally, for all VRU mirror strikes (including where the mirror became detached), the severity of injury was recorded by interrogating the case description to determine whether hospitalisation, on-scene treatment or no treatment was required by the VRU.

The IRIS database contained at total of 27,511 entries for 2015, of which 3,424 entries were found to involve mirror strikes (Table 17). The majority of mirror strikes (60.7%) were found to involve third party vehicles; where a bus mirror strikes a third-party vehicle, or a third-party vehicle strikes a bus mirror. A considerable proportion of mirror strikes (34.7%) were also found to strike an object, whilst only 79 (2.2%) mirror strikes were directly with a VRU. The majority (86%) of VRU mirror strike cases involved pedestrians, whilst only 8 cases were found to involve cyclists and 2 cases involve PTWs.

**Table 17: Frequency of mirror strikes and mirror detachments by object struck in 2015 (data source: IRIS database)**

| Object Struck | Mirror Strikes /n | Mirror Strikes /% | Mirrors Detached /n | Mirrors Detached /% |
|---|---|---|---|---|
| **Third-party vehicles** | 2,079 | 60.7% | 1,291 | 62.1% |
| **Street furniture** | 1,188 | 34.7% | 39 | 3.3% |
| **Pedestrians** | 64 | 1.9% | 11 | 17.2% |
| **Cyclists** | 8 | 0.2% | 0 | 0% |
| **PTWs** | 2 | 0.1% | 0 | 0% |
| **Unknown** | 83 | 2.4% | 1 | 1.2% |
| **Total** | 3,424 | 100.0% | 1,342 | 39.2% |

Of these collisions, 1,342 (39.2%) mirror strikes resulted in the detachment of the mirror. The majority of these cases (96%) were the result of collisions with third-party vehicles, with street furniture and pedestrian mirror strikes making up the remaining cases where a mirror was found to detach.

When considering mirror strikes against street furniture, these cases can be broken down further to give an indication of what street furniture is most likely to be struck by a mirror during operation and what proportion resulted in the mirror becoming detached (Table 18). It is clear from this analysis that the leading cause of mirror strikes against street furniture was through collisions with bus infrastructure, such as bus stops, with 492 (41.4%) cases. This was followed by lamp posts (14.7%), trees (14.5%) and sign posts (8.8%), which make up almost 80% of all such cases.

A total of 39 mirror strikes resulted in the detachment of the mirror from the bus. Of these cases, 28 (71.8%) detachments were caused by collisions with a bus stop, which would be in close proximity to the pedestrians that would be looking to board the bus.

**Table 18: Frequency of mirror strikes and mirror detachments by street furniture object struck in 2015 (data source: IRIS database)**

| Object Struck | Mirror Strikes /n | Mirror Strikes /% | Mirrors Detached /n | Mirrors Detached /% |
|---|---|---|---|---|
| Advertising boarding | 1 | 0% | 0 | 0% |
| Bollard | 1 | 0% | 0 | 0% |
| Bus stop/stand/shelter/pole | 492 | 5.7% | 28 | 5.7% |
| Fence/barrier/railings | 51 | 2.0% | 1 | 2.0% |
| Immobile structure | 2 | 0% | 0 | 0% |
| Lamp post | 175 | 4.6% | 8 | 4.6% |
| Post | 79 | 0% | 0 | 0% |
| Phone box | 5 | 0% | 0 | 0% |
| Road works | 2 | 0% | 0 | 0% |
| Scaffolding | 24 | 0% | 0 | 0% |
| Street furniture | 33 | 0% | 0 | 0% |
| Sign post/road sign | 105 | 1.0% | 1 | 1.0% |
| Traffic lights | 28 | 0% | 0 | 0% |
| Telegraph pole | 9 | 0% | 0 | 0% |
| Tree/branch/bush/hedge | 172 | 0.6% | 1 | 0.6% |
| Wall | 9 | 0% | 0 | 0% |
| Total | 1188 | 3.3% | 39 | 3.3% |

When focussing on the severity of injury experienced by a VRU that was struck by a mirror, it was clear to see that the IRIS dataset did not directly record the severity of injury for each case. To account for this, each case was reviewed to extract information on the treatment history of the VRU following the collision. When considering the 64 pedestrian mirror strike cases, only 8 (12.5%) cases were serious enough to require hospital treatment (Table 19). First aid was provided on scene for 5 (7.8%) cases, whilst no treatment was provided for the remaining cases (assumed that injuries or treatment would be recorded had any occurred).

**Table 19: Recorded treatment for pedestrian mirror strikes (data source: IRIS database)**

| Recorded Treatment | Number of Cases /n | Number of Cases /n |
|---|---|---|
| Taken to hospital | 8 | 12.5% |
| First aid provided on scene | 5 | 7.8% |
| Medical assistance or treatment refused | 11 | 17.2% |
| No treatment required/no injuries | 21 | 32.8% |
| Nothing recorded | 19 | 29.7% |
| Total | 64 | 100% |

When analysing the eight taken to hospital pedestrian cases in greater detail, we find that all 8 cases were admitted to hospital after being struck on the head by a bus mirror (Table 20). Only 3 of these cases, however, directly struck the pedestrian, with the remaining cases typically caused by the mirror becoming detached after striking the bus stop furniture and then striking a pedestrian stood next to the bus stop. Unfortunately, it is unknown what the exact injury severity of these cases would be, as the case notes were not detailed enough to contain this information. Although one can be admitted to hospital for slight injuries, for the purposes of this report, the worst case scenario of all 8 hospital admissions being related to a serious head injury will be assumed.

**Table 20: Case descriptions of pedestrian mirror strikes resulting in a hospital admission (data source: IRIS database)**

| Case Number | Case Description |
|---|---|
| 1 | Head made contact with nearside mirror |
| 2 | Nearside mirror of bus hit pedestrian on head |
| 3 | Nearside mirror hit pedestrian's head |
| 4 | Bus mirror collided with male pedestrian nose as bus was passing crossing |
| 5 | Struck by falling mirror and arm, struck in face |
| 6 | Nearside mirror clipped bus stop and fell into pushchair |
| 7 | Nearside mirror hit bus shelter and fell off bracket causing mirror to fall on pedestrians head |
| 8 | Bus pulled into a stop the nearside mirror hit the bus stop, the mirror to fell off and hit a waiting passenger in the face |

Finally, when considering cyclists and PTWs, no mirror strike cases were recorded as having received any on-scene medical treatment or requiring any hospital admission. Due to this, it is assumed that, despite there being eight cyclist and two PTW mirror strike incidences a year, no such incident results in any injury to the cyclist of PTW.

## 3.9 Summary of Target Populations

The annual target populations estimated for all outcome severities relevant to the VRU impact protection (VIP) and enhanced front end design (FED) for impact protection safety measures (fatal, serious and slight casualties) are presented in Table 21 below. Target populations were considered equivalent between the different VIP and FED safety measure solutions. Target populations were calculated for VRUs (pedestrians, cyclists and PTWs), as this is the population affected by improvements in the VIP and FED safety performance of buses. The selection of appropriate target populations included the average annual number of bus collisions in London involving VRUs, where the VRU impacted the front end of the bus. All data was abstracted from the UK STATS19 road safety database.

**Table 21: Estimated average annual target populations for the VRU impact protection [VIP] and enhanced front end design [FED] for impact protection safety measure solutions (data source: STATS19)**

| Casualty Type | Outcome Severity | | |
|---|---|---|---|
| | Fatal Casualties | Serious Casualties | Slight Casualties |
| Pedestrians | 6.9 | 45.8 | 144.9 |
| Cyclists | 0.5 | 3.9 | 27.0 |
| PTWs | 0.2 | 2.8 | 13.1 |
| **Totals** | **7.6** | **52.5** | **185.0** |

In addition to this top level target population data, this analysis of the collision landscape found a number of key collision characteristics that could be used to support development of future testing and assessment protocols. These include:

- VRU collisions may be located across the front end, although 60% of impacts are with the outermost 500 mm of the bus front end at the nearside and offside edges
- Buses are typically manoeuvring in a straight line (going ahead other, moving off or slowing or stopping) when involved in collisions with VRUs
- Pedestrians are typically crossing the road, predominantly from the nearside of the bus, when involved in collisions with buses
- Cyclists and PTWs are typically involved in rear-end or head-on collisions with buses whilst either stationary or manoeuvring in a straight line
- Buses may be travelling at speeds between 0-50 kph when involved in a collision with VRUs, with 80% of collisions occurring at speeds greater than 11 kph (Figure 5)

The annual target populations estimated for all outcome severities relevant to the VRU run-over protection (VRP) and enhanced front end design (FED) for run-over protection safety measures (fatal, serious and slight casualties) are presented in Table 22. Target populations were considered equivalent between the different VRP and FED safety measure solutions. Target populations were calculated for VRUs (pedestrians, cyclists and PTWs), as this is the population affected by improvements in the VRP and FED safety performance of buses. The selection of appropriate target populations included the average annual number of bus collisions in London involving VRUs, where the VRU impacted the front end of the bus, divided by the proportion of fatal collisions resulting in a run over event. Data was abstracted from the UK STATS19 road safety database and from Edwards *et al*. (2018).

**Table 22: Estimated average annual target populations for the VRU run-over protection [VRP] and bus front end design [FED] for run-over protection safety measure solutions (data source: STATS19 and (Edwards *et al.*, 2018))**

| Casualty Type | Outcome Severity | | |
|---|---|---|---|
| | Fatal Casualties | Serious Casualties | Slight Casualties |
| Pedestrians | 2.3 | 15.3 | 48.3 |
| Cyclists | 0.2 | 1.3 | 9.0 |
| PTWs | 0 | 0.9 | 4.4 |
| **Totals** | **2.5** | **17.5** | **61.7** |

Finally, the annual target populations estimated for outcomes relevant to the mirror strike (MST) safety measure (fatal, serious and slight casualties and damage only collisions) are presented in Table 23. Target populations were considered equivalent between different MST safety measure solutions. Selection of appropriate target populations was performed to include the average annual number of bus collisions in London involving VRUs where the VRU was struck by the mirror of a bus and the average annual number of bus collisions in London involving damage-only mirror strikes. Data was abstracted from the IRIS database.

**Table 23: Estimated average annual target populations for the mirror strike [MST] safety measure solutions (data source: IRIS database)**

| Casualty Type | Outcome Severity | | | |
|---|---|---|---|---|
| | Fatal Casualties | Serious Casualties | Slight Casualties | No Injury |
| Pedestrians | 0 | 8 | 5 | 51 |
| Cyclists | 0 | 0 | 0 | 8 |
| PTWs | 0 | 0 | 0 | 2 |
| Damage-Only | 0 | 0 | 0 | 3,350 |
| **Totals** | **0** | **8** | **5** | **3,411** |

# 4 Solution Definition

## 4.1 Introduction

The purpose of this section is to review the range of technologies and approaches available for the VRU Frontal Crashworthiness (VCW) safety measure to use as potential solutions. This will be achieved by summarising the range of relevant technologies and approaches for the Front End Design (FED), VRU Impact Protection (VIP), VRU Run-Over Protection (VRP) and Mirror Strike (MST) safety measures. The potential solutions summarised by this review will therefore be used to provide background information on the future safety measure solutions that may be implemented by the Bus Safety Standard (BSS).

The range of technologies and approaches identified as relevant to the FED, VIP, VRP and MST safety measures may be split into several functional safety measure solutions, including:

**Enhanced Front End Design (FED)**

- Vertical raking
- Horizontal curvature
- Geometric Design Requirements
- Other factors to consider

**VRU Impact Protection (VIP)**

- Repositioning of cab components
- Energy absorbing structures

**VRU Run-Over Protection (VRP)**

- Run-over guards
- Deployable run-over airbags

**Mirror Strikes (MST)**

- Camera monitor systems
- Energy absorbing mirrors
- Repositioning of mirror components
- Visual conspicuity

Each of these safety measure solutions have been reviewed in the following sections. The technical background for each solution has been summarised, before critically appraising its relevance to the BSS and identifying the future developmental timeline. Finally, this section reviews the important human factors elements that need to be considered before the implementation of any potential safety measure solution.

## 4.2 Enhanced Front End Design (FED)

The majority of current bus models adopt cube-like designs. Recent models feature rounded edges in their design; however, more could still be done to the cab geometry to improve Vulnerable Road User (VRU) frontal crashworthiness. Improving the bus cab profile could be achieved through a number of different approaches. This may include introducing vertical raking (i.e. increasing the angle of the front end of the bus from vertical, e.g. Optare Solo), horizontal curvature (i.e. rounding the edges of the bus front end, e.g. Wrightbus New Routemaster) and VRU deflecting wheel arches (e.g. Volvo ECB) (Figure 7).

**Figure 7: Optare Solo (left) Wrightbus Routemaster (centre) and Volvo Environmental Concept Bus (ECB) (right)**

### *4.2.1 Vertical raking*

The vertical raking of the front end of a bus involves designing the front face of the bus at an angle to the vertical plane to create a sloped design (e.g. the Optare Solo in Figure 7 above). VRU safety may also be enhanced through the localised raking of critical zones on the front end of the bus, including above the front bumper and the wheel arches (e.g. the Volvo ECB in Figure 7 above). By increasing the raking of the bus front end, the lower body of the VRU is struck prior to the upper body. This has two clear risk reduction benefits in both delaying the impact of critical body regions and the lifting of the VRU upwards away from the floor.

The delay in impact between the critical body regions of the VRU (e.g. the head) is caused by the raked front end of the bus progressively impacting the legs, torso and then, eventually, the head of the VRU. This would decrease the peak accelerations experienced by the head, as a greater proportion of the impact energy is dissipated across other body regions. This, in turn, would decrease the risks of serious brain injuries.

Vertical raking may also be used to apply impact forces that lift the VRU away from the floor. Impact forces that have a significant vertical element to them (i.e. caused by the raked front end), and that can overcome the forces of gravity acting on the VRU, will lift the VRU away from the floor to reduce the likelihood of the VRU being run-over by the bus. The closer the bus front end raking is to the vertical plane, the less likely it is that the vertical element of the impact forces will large enough to lift the VRU away from the floor. However, should the impact point be above the centre of gravity of the VRU, this could result in the impact forces pushing the VRU toward the ground.

Raking does, however, have a number of safety disadvantages that should be considered in the front end design of a bus. Should the rake angle become too large, this could result in an increase in head impact velocities and rotational head accelerations, as the upper body of the VRU is accelerated around the bumper to produce a whiplash like impact against the bus front end. Raking is likely to also increase the risks of more severe leg injuries, as this body region will potentially experience higher loads during impact when compared to flat fronted buses. In addition, greater rake angles could also potentially throw VRUs higher and further during impacts, which may increase injury risks during the secondary impact with the road. Clearly, it is likely that there is a range of rake angles that optimise the safety of a VRU when compared to the current generation of designs.

### *4.2.2 Horizontal curvature and tapering*

The horizontal curvature and tapering of the bus front end involves designing the front end to have 'radiused' edges, rounded front end or tapered nosecone designs (e.g. Wrightbus New Routemaster in Figure 7 above). By introducing horizontal curvature or tapering at the edges of the bus front end, the bus delivers a lateral force to the VRU during an impact that aims to deflect the VRU away from the pathway of the bus. This has a clear risk benefit in that this design feature may be employed to reduce the likelihood of run-over event occurring.

Several different factors exist, however, that could affect the effectiveness of this safety measure solution, including the radius of curvature, the tapering angle and the lateral point at which the rounding or tapering begins. The smaller the radius of curvature is, the stiffer the structures will be for a given material at a particular impact point and the more likely it is that the thorax or shoulder of the VRU will not fully engage with the front end of the bus prior to the impact with the head. This issue is also seen by the tapering angle, with greater angles decreasing the likelihood of full engagement between the front end of the bus and the VRU shoulder and thorax.

Should the shoulder or thorax of a VRU not fully engage with the bus front end during a collision, greater impact energies are likely to be transferred to the head, thus potentially increasing the risks of a serious brain injury. The point at which the horizontal curvature or tapering begins also affects the coverage of this particular safety measure, with more lateral points resulting in a smaller area of potential interaction. Finally, the lateral deflection of the VRU needs to be controlled to ensure that the VRU is not deflected into the path of other vehicles or other street furniture. Again, it is clear there are a range of design criteria that could optimise the safety of a VRU when compared to the current generation of designs.

### *4.2.3 Geometric Design Requirements*

Research in bus-to-VRU impacts, and run-over protection, is still in its early stages. Valuable lessons can be learnt from other industries with established VRU protection guidelines. Trams previously shared the same cube-like designs, operating environments and travel speed as buses. With a recent overhaul of guidelines underpinning safer tram front end designs, the STRMTG (2016) has developed a design guide that intends to improve the front end design of trams to reduce injury risks and minimise the risks of run-over events. This guide specifies that the front end of a tram must be designed to laterally deflect pedestrians during impacts.

To achieve this, the front end must have an angle of at least 15° in the horizontal plane (α) from a point 150 mm either side of the centreline of the tram and an angle of at least 30° from a point 300 mm inward from the edge of an impact surface, defined based on the edges of the main pillars at a height of 1.75 m. In addition to requirements for curvature in the horizontal plane, STRMTG also provide requirements for vertical raking (β) based on both the horizontal curvature of the front end design and which part of the tram is being assessed (i.e. windscreen (ws) or bumper (streamlining)). This is combined with a requirement for the outer most points of the front end, which should have the lowest Z (vertical) coordinates possible to ensure pedestrians are hit below the knees (i.e. ≤ 350 mm). Finally, within the impact surface area, sharp edges and protruding components must have a minimum radius of 6 mm (10 mm recommended) or be covered (e.g. flood lights and wiper bosses).

A simulation investigation conducted by (Weber *et al.*, 2015), including 31 simulated tram-to-VRU collisions at speeds of up to 30 km/h. assessed different methods of optimising the tram front end design. The study recommended the front trim panel of a tram should have a minimum ground clearance of at least 250 mm while fully laden to allow partial run-over of a 50$^{th}$ percentile adult male without crushing. This should be reduced to between 50-80 mm closer to the axle to prevent contact with the wheel. The design and positioning of structural components that extrude below the 250 mm in the partial run-over zone should also be considered. To allow time for the deceleration before impact and reduce head injury severities, a minimum windscreen base height of 1300 mm is recommended, as well as an 80-100 mm offset between the front trim panel and the windscreen. Finally, the lower section of the front trim panel should be almost vertical to avoid applying forces that accelerate VRUs (especially children) towards the ground (Weber *et al.*, 2015).

#### *4.2.4 Other factors to consider*

The introduction of design requirements for the front end geometry of the bus may have a number of important consequences for some of the key functions of the bus. These could include the potential introduction of longer vehicles, the reduction of the passenger carrying capacity, the relocation and restructuring of the driver cab and the repositioning of the door.

Introducing raked and curved bus front end designs may extend the length of a bus. Should longer buses be introduced, special care should be given to ensuring that additional length does not conflict with Council Directives 96/53/EC and 2002/7/EC, Directive (EU) 2015/719 or Regulation (EC) 1230/2012, which define the fundamental design envelope for buses (see further details in Section 7.2). It is likely, however, that a significant proportion of the fleet will be able to increase vehicle lengths by over 1 m without conflicting with maximum length or turning circle requirements, particularly if curved bus front end designs are adopted. Bus length extensions may, however, conflict with current stabling requirements. Introducing longer buses, even if increased by a small extension, may result in issues for depots where stabling space is at a premium, thus resulting in a reduction in the capacity of bus depots in London. The introduction of a safety measure that lengthens buses will therefore potentially incur greater costs relating to increased operational costs and capital costs for new depots.

Raked and curved bus front end designs may also be introduced without any increase to the overall length of the bus (i.e. by subtracting from the design space available to the bus by curving and raking backward from the foremost point of the bus front end). Whilst this will certainly avoid the issues associated with bus length extensions, this may also result in other important issues. These include a potential reduction in bus capacity, with both the vertical raking and horizontal curvature likely to take away from upstairs passenger seating space and downstairs passenger standing capacity. The extent that this removes from the capacity of the bus will clearly be dependent on the extent of the requirements placed on the raking and horizontal curvature of the bus front end.

Raking and curving the front end of the bus, whether by subtraction or extension, could also impact other aspects of the design of the bus. The front doors may have to be repositioned to a more rearward location to account for the curvature of the front end, which in turn may affect passenger flow and dwell times at bus stops. The driver cab could be redesigned to be more centrally located (e.g. similar to a tramway cab), improving the direct vision of the driver to the nearside of the bus and increasing the available driver cab space (although this may create more of a barrier driver/passenger interaction). Finally, care must be taken to ensure that bus-to-vehicle crashworthiness compatibility is not compromised by design requirements that disbenefit bus drivers or other road users (e.g. a greater number of car occupants injured by greater intrusion into the vehicle by highly curved bus front ends).

## 4.3 VRU Impact Protection (VIP)

### *4.3.1 Repositioning of cab components*

Repositioning certain bus cab design features to avoid areas of the bus which are more likely to be involved in an impact is one proposed solution. This may contribute to a reduction in the severity of injuries during a collision by ensuring that stiffer bus components or bus components with a small radius of curvature are removed from the area of greatest risk in regards to the likely point of impact for a VRU. Components of a bus that could potentially be repositioned include the windscreen wiper bosses and the A-pillars.

The function of a windscreen wiper boss is to cover the spindles (the component that moves the wipers). As spindles are stiff and relatively small, these can cause serious injury to VRUs if directly impacted. Modern double deck buses typically have their wipers mounted above the windscreen to prevent this from occurring; however, models still exist where the bosses are mounted below the windscreen (see Figure 8). Single deck buses, on the other hand, typically have bosses mounted under the windscreen; however, newer models also adopt an above windscreen mounting position (see Figure 8). In the automotive industry, spindles are usually positioned in the middle of the base of windscreen and are typically covered by the scuttle to prevent the head directly impacting them. Several car models also designed their wiper spindles to be located at the base of the A-Pillars to reduce any additional injury risks.

**Figure 8: Various windscreen wiper mounting positions for double and single deck buses**

**The A-pillars of a vehicle are a key structural component and, as a result of this, also one of the stiffest. A number of manufacturers have moved the A-pillars on their latest generation of bus models rearwards (see**

Figure 9). This was implemented primarily to improve driver vision, but may also effect VRU impact protection. By moving the stiffer A-pillars rearwards and introducing a wraparound windscreen, the energy absorbing properties at the corner of the bus may have been improved. Using curved glazing may, however, have increased the stiffness of the glazing. As the combined effects of adopting this approach remain unknown, it is important to perform a further literature review to better understand its effectiveness.

**Figure 9: Wrightbus Gemini 2 (left) and Gemini 3 (right) models**

### *4.3.2 Energy absorbing structures*

The adoption of improved energy absorbing structures could be used to greatly reduce the risks of injury by reducing the loads experienced by a VRU during a collision. This may be achieved through the increased use of materials with improved energy absorbing properties (e.g. glazing or expanded polypropylene/polystyrene (EPP/EPS)) to cover stiffer structures or through more active technology such as VRU airbags.

Key areas of a bus front end which may benefit from improved energy absorption structures include the windscreen, the nearside and offside corners, the bumper, the windscreen wiper bosses and the A-pillars. When designing buses for VRU safety, however, it is also important to consider the unintended consequences on road users such as car and bus occupants. By making the bus front end less stiff to improve VRU safety, the crashworthiness structures of the bus may not be able to dissipate energy as effectively in collisions with other vehicles, potentially resulting in greater levels of intrusion into the vehicles. It is therefore important to ensure that VRU safety is improved, but not at the cost of the safety of other road users.

A VRU airbag functions in a similar way as an internal airbag, but is deployed externally from underneath the bonnet or windscreen base to prevent VRU heads from directly striking the stiffer structural features of a vehicle. VRU airbags are currently equipped to a small number of cars (Land Rover Discovery Sport, Subaru Impreza and Volvo V40) and are in the study phase for fitment on HGVs (Volvo Cars , 2017;Radu, 2016;Kimberly, 2015).

To maximise inflation time prior to the impacting of critical body regions against the vehicle, sensors or triggers are typically fitted to the front bumper. This is a potential issue for flat fronted vehicles, such as buses, as there is less time between the initial impact with the VRU and the impact between the head/thorax and the structures of the bus when compared to bonneted vehicles such as cars. This may therefore result in a partially inflated airbag during a collision, so resulting in an inadequate level of protection.

One method of reducing inflation time could be to install multiple smaller airbags in critical locations such as the front corners, where Autonomous Emergency Braking Systems (AEBS) are less effective at detecting potential collisions, instead of a full width system. Another key factor with VRU airbag installation and coverage is that a sufficient proportion of the bus windscreen must remain uncovered to allow the bus driver to see where they are going.

## 4.4 VRU Run-Over Protection (VRP)

### *4.4.1 Run-over guards*

Run-over guards are devices fitted to vehicles with high ground clearance (e.g. Heavy Goods Vehicles (HGV)) to prevent VRUs from being killed by the axle or being pulled underneath the vehicle after the initial collision. Devices can be fixed or articulated. Fixed guards take the form of a panel, singular bar, multiple bars or a combination of panels/bars depending on the vehicle it intends to cover. Fixed run-over guards are, however, highly dependent on the topography of the route and operational requirements of the service. Fixed run-over guards would therefore only be appropriate for relatively flat routes that do not require the kneeling function for improved accessibility (i.e. additional infrastructure changes would be required).

Articulated side run-over guards have been introduced on to some G variant (off road) HGVs (see Figure 10). These devices allow the guard to move when impacted in certain orientations, thus enabling the guard to pass over rough terrain without impacting the operation of the vehicle. This design could be beneficial to the front and sides of buses that use the kneeling function to improve passenger accessibility or operate on routes with specific traffic calming measures (e.g. speed humps).


**Figure 10: Articulated side run-over guards**

When considering the approaches adopted by comparable industries, Clause 278 of the UK Office of Rail Regulation (ORR) “Guidance on Tramways - Railway Safety Publication 2” sets out a minimum level of pedestrian run-over protection that tram designs must be approved to (ORR, 2016). This includes continuous protective skirting around the sides and ends of the vehicle, which is designed to deflect people away from the vehicle and prevent run-overs. In exceptional cases where the skirting does not provide adequate protection due to the route topography, a guard should be installed in front of the leading wheels. This guard should be as close to the road surface as possible. It may have a deflecting lower edge made of pliable material to minimise the gap between it and the surface of the road.

An unintended consequence of equipping a bus with frontal run-over guards is increasing the risks associated with VRUs being deflected towards nearby road users (e.g. cars) or road furniture. Run-over guards will also increase the gross vehicle weight of the bus design.

### *4.4.2 Body catcher device*

A body catcher device would fulfil a similar function as a run-over guard. Body catchers are, however, typically fitted to the undercarriage of a vehicle and directly in front of the first axle to prevent the VRU from making contact with the front axles in the event of a run-over event. Body catcher devices may be either fixed or deployable. A fixed device is the simplest body catcher and often takes the form of a bar or series of bars. Depending on the route typography, however, fixed systems may not provide an adequate level of ground clearance to prevent run-overs (e.g. when driving over the crest of a hill). Deployable body catchers would be activated by sensors

### *4.4.3 Deployable run-over airbags*

Inflatable frontal VRU run-over guards are not currently fitted to any road vehicles, but are in the developmental phase of being fitted to trams operating in busy urban environments (Bombardier, 2015). Bombardier's Bodyguard inflatable guard works alongside short and long range VRU detection systems and Autonomous Emergency Braking Systems (AEBS). If an unavoidable collision is detected, the guard deploys from underneath the front of the tram and fills the gap to prevent the VRU from being run-over if a collision is unavoidable.

## 4.5 Mirror Strikes (MST)

Mirror strikes can cause serious head injuries to VRUs travelling in close proximity to buses. By replacing the mirrors with camera monitor systems, improving the energy absorbing properties of the mirrors, repositioning the mirror clusters away from key collision zones or improving conspicuity of the mirror cluster, the risks of injury could be reduced.

### *4.5.1 Camera monitor systems*

Regulation 46 (R46: Indirect Vision Devices) specifies minimum requirements for the ground plane a driver must be able to see through the use of indirect vision devices (e.g. mirror or camera monitor systems (CMS)), alongside the requirements for the installation and testing methods (UNECE, 2016). CMS can therefore be used to replace all seven classes of mirror, as long as they provide at least the same visibility of the ground plane and meet the minimum requirements set out by R46. CMS are advantageous, with regards to mirror strikes, as they do not protrude as far from the exterior of the bus (see Figure 11) and their monitors can be installed internally within the driver cab. Future CMS installation guides could adopt greater mounting heights to avoid VRU impacts and require CMS cameras to be mounted such that they extend no further than a specified distance away from the edge of the vehicle. Rather than mitigating injury severity, this approach would prevent both VRUs and street furniture from being struck by bus mirrors. This could therefore present both societal and operational cost savings to both TfL and bus operators. For further information on CMS, (Huysamen *et al.*, 2019) (Martin *et al.*, 2018).


**Figure 11: A trial bus equipped with CMS**

### *4.5.2 Energy absorbing mirrors*

Improving the energy absorbing properties of wing mirror clusters could be achieved using two different methods; improved casing design and/or deformable mirror mountings. Both solutions could improve the outcome of an interaction by reducing the linear accelerations experienced by the VRUs head. A more energy absorbent wing mirror cluster casing is the least complex solution; however, should this result in increased mirror cluster sizes, this may impact the field of vision of the driver and increase mirror strike rates. A deformable mirror mounting, also known as knock-back mirrors, would be less disruptive to driver vision, but could be more vulnerable to operational damage from street furniture. The mounting would have to be strong enough to withstand these obstacles yet flexible enough to minimise any injuries to VRUs. There are a large number of mirror and mirror mount combinations available for mounting to the bus. It is currently unknown, however, if any of these mirror combinations have been specifically designed to be safer during VRU mirror strikes.

### *4.5.3 Repositioning of mirror components*

An alternative approach is to reposition the mirrors so that they are positioned above the head height of a pedestrian walking on the pavement close to the side of the bus. R46 states that an indirect vision device must not protrude any further than necessary to achieve the vision requirements for its relevant class (UNECE, 2016). Specifically, if the lower edge of a Class II (to VII) mirror is less than 2 m above the ground, when the vehicle is at its maximum laden weight, the mirror cannot extend further than 250 mm beyond the overall width of the vehicle, excluding mirrors. To achieve improvements in VRU safety, mirrors could be encouraged to be mounted at greater heights or closer in to the vehicle bodywork. Whilst this would be a reasonable solution for VRU safety regarding mirror strikes, this may result in a number of unintended consequences. By mounting mirrors at a greater height, driver visibility of the mirrors may be obstructed by the window frame and, should the bus be manoeuvring on a significant cross slope, the mirror may actually extend a greater distance towards the pathway, thus increasing the likelihood of mirror strikes against other roadside furniture.

### 4.5.4 Visual conspicuity

Another technique for reducing mirror strikes is to increase the visual conspicuity of the mirrors. This could be achieved by changing the colour of the wing mirror cluster to make it more conspicuous to VRUs. It is a current TfL requirement, however, for wing mirror clusters to be painted in yellow, which has been shown to be a highly conspicuous colour due to the human eye being most sensitive to yellow-green wavelengths (Gross *et al.*, 2008).

## 4.6 Human factors considerations

The redesign of a bus to reduce the impact of collisions with other road users provides clear potential benefits. However this has the potential to cause some unintended shifts in driver and VRU behaviour. The evidence for so-called behavioural adaptation (when users reduce some of the safety benefit of an intervention through changes in behaviour) is, however, uncertain. Behavioural adaptation has not previously been researched within the specific context of the VCW safety measure. To truly understand the effects of shifts in behaviour, one would need to understand if the reductions in injury likelihood were outweighed by the impact of any unintended negative consequences from behavioural adaptations.

### 4.6.1 Drivers

Drivers may be more willing to take risks to reduce the time their route takes, if they feel that doing so provides benefits that outweigh the increased potential risks of hitting a VRU (e.g. drivers under time pressure may drive closer to kerbs to reduce their turning radius at corners to make journeys quicker). Incidences of riskier driver behaviour may increase if the drivers feel that the new bus designs associated with improved VRU frontal crashworthiness help mitigate the risks they had previous accepted when making a decision on how to drive.

If we view this within the context of knowledge about risk acceptance, there may also be individual differences to consider. For example Josephs et al. (1992) showed that individuals with high self-esteem were ten times more likely to select a riskier gamble due to self-belief, often stemming from positive past experiences. In situations where drivers felt they need to make up time on a route because they were running late, individuals who have higher self-esteem may therefore be more likely to take greater risks (Rudin-Brown and Jamson, 2013).

When considering the safety measure solutions proposed for the VCW safety measure, it is clear that a number of safety measure solutions could result in drivers performing higher risk manoeuvres. These include: raked/curved front end designs, the introduction of energy absorbing structures/mirrors, the replacement of mirrors with CMS and the repositioning of mirrors. Although difficult to predict the exact behavioural changes that may result from these solutions without a specific on-road trial, should drivers feel that new bus front end designs, mirror designs or CMS help mitigate the likelihood or consequences of a collision they may adopt riskier behaviours such as driving closer to curbs, driving closer to VRUs and driving at faster speeds round corners and bends.

#### 4.6.2 Vulnerable road users

The behaviour of VRUs in close proximity to buses may also be affected by the introduction of a new safety measure solution. The impact of such solutions on the risk taking behaviour of VRUs should therefore also be considered, in particular how comfortable they are with travelling at closer distances to a bus and whether there is an increased risk acceptance whilst manoeuvring around buses. Should VRUs feel that they are offered greater impact protection (i.e. through energy absorbing structures/mirrors or raked/curved bus front end designs) or that the likelihood of being involved in an collision has reduced (i.e. through the replacement of mirror clusters with CMS or the repositioning of mirrors), then they may feel more comfortable taking greater risks around a moving bus.

When considering the specific solutions proposed for the VCW safety measure, it is again difficult to predict exact behavioural changes resulting from implementing these solutions without a specific on-road trial. Higher risk behaviours that may be adopted could include: VRUs manoeuvring closer to the edges of the bus with the replacement of mirror clusters with CMS or repositioning of mirrors, highly curved bus front end designs resulting in VRUs beginning to cross the road from behind the driver ocular point when the bus is stationary and VRUs taking greater risks with crossing the road when the bus is moving at speed due to perceived greater protection from energy absorbing structures and raked/curved bus front end designs.

#### 4.6.3 Human factors solutions

One way of deterring either VRUs or bus drivers from manifesting high risk behaviours is to use the innate tendency of individuals to display loss aversion (i.e. people are more sensitive to potential loss than potential gain). In a situation where there is a 50-50 probability, the potential gain must be approximately twice the value of the potential loss to an individual for them to be willing to accept the risk (Kahnemann, 2003;Tversky and Kahneman, 1992). If such a finding holds true in the context of the VCW safety measure, to deter drivers and VRUs from displaying higher risk behaviours, the repercussions for being caught displaying deviant behaviour might therefore need to be significantly higher than the benefits that these behaviours have the potential to provide. The manner in which this is achieved would need to be carefully considered (e.g. jaywalking laws in North America might be considered the extreme, while verbal warnings and training for those exhibiting such behaviours might be a less extreme example). Ultimately, without evidence from specific on-road trials to investigate how VRU and driver behaviours change with the implementation of these safety measure solutions, it is very challenging to predict future behaviour changes. Future on-road trails should therefore be considered for safety measure solutions where there is significant concern over whether behavioural changes will undermine its effectiveness.

### 4.7 Summary of Feasible Solutions

The previous sections specified the safety measure solutions for four secondary safety measures: Enhanced Front End Design (FED), VRU Impact Protection (VIP), VRU Run-Over Protection (VRP) and Mirror Strikes (MST). This state-of-the-art review found that each secondary safety measure has several viable safety measure solutions. Each solution has several advantages and disadvantages, discussed in full in this section, that result from the relative complexities in their designs and implementation and from interactions with current operational and roadside infrastructure. Please find below the finalised list of all feasible VCW related safety measure solutions that will be carried forward to the future stages of the review:

**Enhanced Front End Design (FED)**
- Geometric Design Requirements

**VRU Impact Protection (VIP)**
- Repositioning of Windscreen Wipers
- Energy Absorbing Structures

**VRU Run-Over Protection (VRP)**
- Deployable Run-Over Guards

**Mirror Strikes (MST)**
- Class II Mirror CMS Replacement
- Energy Absorbing Mirrors

Section 5 will consider the evidence underpinning the relative effectiveness of each safety measure solution to direct future efforts towards the most effective solutions.

# 5 System Performance

## 5.1 Introduction

The purpose of this section is to perform a review of the effectiveness of the VRU Frontal Crashworthiness (VCW) safety measure solutions discussed in Section 4. The effectiveness of a safety measure solution is determined by how well the particular 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 (or damage only collisions that could be prevented or mitigated), should the particular safety measure solution be implemented across the entire fleet.

The purpose of the following subsections is to review the effectiveness of the range of the VCW safety measure solutions previously reviewed in Section 4. The following subsections therefore review the current evidence base underpinning the estimation of effectiveness values for each of these safety measure solutions. A summary of overall effectiveness values may then be found in Section 5.6 in the final summary subsection.

## 5.2 Enhanced Front End Design (FED)

The implementation of enhanced front end designs for HGV cabs was made possible through UNECE Directive 2015/719 (amending Council Directive 96/53/EC), which granted a derogation in HGV cab lengths providing this improves VRU safety, aerodynamics and driver comfort (UNECE, 2015).

Although there are no production HGVs with enhanced front end designs currently available on market, several research projects have attempted to quantify the potential effectiveness of this approach for VRU safety. One such example is the Advanced PROtection SYStems (APROSYS) project, which ran from 2004 to 2010 and investigated the underlying causes of collisions and crashworthiness of a variety of different vehicles (Department for Transport, 2011). The APROSYS project was split into several vehicle based sub-projects, including one heavy vehicles sub-project which was applicable to HGVs (SP2). This sub-project comprised of two relevant tasks; Task 2.1.1 “Development of the Heavy Vehicle Aggressivity Index” (see Sections 7.3.3 and 7.4.1) and Task 2.1.2 “Pedestrian/Cyclist friendly frontal and side design strategies and concepts” (Gugler, 2009). During Task 2.1.2 a wide range of innovative safety solutions were devised and assessed (Bovenkerk and Fassbender, 2006). Out of the many proposed solutions, two successful solutions were taken forward to the testing stage: the nose cone and safety bar concepts (Feist and Faßbender, 2008).

Using data collated during the APROSYS project, Welfers *et al*. (2011) predicted a potential reduction of VRU fatalities involved in interactions with the cone-shaped FKA concept truck when compared to a traditional cube like HGV cab (see Figure 18). Part of this investigation included comparing HGV design collision performance by simulating HGV to VRU collisions. During a series of simulations, 6 year old child, 5% female, 50% male, 95% male and cyclist models were simulated striking the centre and edge of both vehicles (Welfers *et al.*, 2011).

VRU run overs were 100% prevented in nine different collision scenarios involving the FKA concept truck, whilst the reference HGV ran over the VRU in 66% of these collision scenarios (Welfers *et al.*, 2011). When evaluated against the reference HGV, the FKA concept, with its 0.8 m enhanced front end design, Welfers *et al*. (2011) assumed the design to be 70% effective at preventing VRU fatalities when travelling at speeds of ≤40 kph, 30% effective when travelling between 40-50 kph and 0% effective when travelling above 50 kph. When summarising this, Welfers *et al*. (2011) predicted that an 0.8 m enhanced front end design would prevent 232-296 fatalities a year, relating to an effectiveness range of 42-63%.

An investigation carried out by Robinson *et al*. (2010) provided an initial assessment of the likely feasibility, regulatory implications, costs and benefits of introducing extended Truck Front End Designs (TFED) to HGVs. The study assessed the impact this design change could have on light and heavy vehicle occupants, VRUs and vehicle performance (aerodynamics and manoeuvrability). Part of this involved calculating the number of VRU fatalities that could be prevented annually in GB by introducing extended TFEDs of various lengths in to the fleet. The study estimated an increase of 0.2 m could prevent 15% of VRU fatalities, 0.5 m prevented 29% of fatalities and 1 m prevented 47% of fatalities.

Martin et al. (2017) conducted a cost-benefit analysis to establish the cost-effectiveness of a range of clustered safety measures associated with regulating the VRU safety performance of HGVs that adopt cab extension exemptions permitted by Directive (EU) 2015/719. One of the safety measures under consideration included looking at the VRU impact protection provided by an extended TFED. To achieve this, the study included the 0.5 m and 1.0 m extension effectiveness values from Robinson et al. (2010) and Welfers et al. (2011) (29%-47% and 42%-63% reduction in fatalities respectively) then paired the two upper estimates and two lower estimates together to create a best-in-class (47%-63%) and mid-range (29%-42%) effectiveness estimate range (see Table 24). These ranges were assumed to be transferable to serious injuries as no further research could be found to separate this injury severity level (Martin *et al.*, 2017).

**Table 24: Estimated overall effectiveness of the best-in-class and mid-range designs for the TFED VRU impact protection safety measure, table adapted from (Martin *et al.*, 2017)**

| Collision Partner | Best-in-Class Extension (1.0 m) | | Mid-Range Extension (0.5 m) | |
|---|---|---|---|---|
| | Fatals (%) | Serious (%) | Fatals (%) | Serious (%) |
| **Pedestrian** | 47-63 | 47-63 | 29-42 | 29-42 |
| **Cyclists** | 47-63 | 47-63 | 29-42 | 29-42 |

Hamacher *et al.* (2012) conducted a series of simulated car to pedestrian interactions using a variety of different vehicle configuration categories (compact, sedan, van (MPV), sports car, SUV and “one box”) to evaluate post-impact pedestrian kinematics.

The investigation simulated pedestrians walking out in front of the vehicles and being struck at 20, 30, 35 and 40 kph (Hamacher *et al.*, 2012). Six year old child, $5^{th}$ percentile female, $50^{th}$ percentile male and $95^{th}$ percentile male computational models were set up in two different walking stances, then struck at five different impact points along the width of the vehicle. A deceleration of 0.8 *g* was applied to vehicle models as well as a 2.5º incline to the vehicle front to represent brake dive.

This study found the "one box" design (comparable to a 58.8° raked bus front end) resulted in the greatest launch speeds and furthest throw distances, regardless of pedestrian size (Hamacher *et al.*, 2012). This is primarily due to the higher bonnet leading edge (BLE) and steeper bonnet rake angles, which result in large transfers of forward energy during a collision (i.e. pedestrian does not ride up and roll over bonnet and roof).

The flight altitude varied depending on the human model (Hamacher *et al.*, 2012). The average flight altitude of the six year old child and $5^{th}$ percentile female models were much lower than that of the $50^{th}$ and $95^{th}$ percentile male models due to the geometry of the vehicles with a higher bonnet leading edge directing the lower centre of gravities of the smaller dummy model downward rather than up.

The study also analysed the likelihood of secondary impacts on the vehicle (Hamacher *et al.*, 2012). To do this the vehicle deceleration was reduced to 0.5 *g* and the vehicle incline (representing brake diving) removed. One box vehicles were found to have the lowest probability of this occurring (less than 20%), primarily due to the much greater forward throw distances. In early tests conducted at deceleration rates of 0.8 *g*, secondary impacts did not occur.

Whilst this study provides a useful insight to how much impact kinematics can vary between groups of similar sized vehicles with different front geometries, the results from this study are not directly transferrable to a typical bus due to the difference in shape and size of the vehicles. The one box front end design, however, provides a number of interesting results for this project. The bonnet angle of 30° provides an insight to the mechanics of an impact occurring against a more steeply raked vehicle front end, showing that the more steep the rake the further a VRU will be thrown. It also highlights the risk that, as the raking of the front end tends towards vertical, VRUs could be thrown straight towards the ground, thus increasing the risk of run-over events. Future designs should therefore try to encourage optimised raking levels that balance run-over risk and throw distances.

It is recommended, therefore, that the BSS adopts two geometric design requirement levels for assessing the risks of head injury and run-over. These include a minimum performance requirement that represents the current best practice performance of the current fleet and an optimised performance requirement that represents the best performance possible with the front end design of a bus. A star rating scheme may be used to rank performance levels between these two requirements. Due to the paucity of research, however, it is important to perform research to understand how bus front end raking and horizontal curvature affect head injury and run-over risk. It is recommended that a parametric computational modelling study be performed to evaluate the optimal combination of these design variables.

## 5.3 VRU Impact Protection (VIP)

### 5.3.1 Repositioning of windscreen wipers

The requirements for the repositioning of the windscreen wipers would require windscreen wiper bosses to be located above the windscreen of the bus. This would result in 100% of collisions with the rigid wiper bosses being prevented. This would, however, only reduce the injury severity of such collisions by a single level, as the VRU would still impact the front end of the bus. This impact is likely to be significantly more distributed in its loading of the VRU, so is likely to be not as harmful to the impacted VRU.

### 5.3.2 Energy absorbing structures

The APROSYS Safety Bar concept is a retrofit expanded polypropylene (EPP) structure which can be fitted to the front of a HGV to reduce the risk of injuries to the head and lower extremities at impact speeds of up to 40 km/h (EPP bottoms out in collisions above this speed) (Feist and Faßbender, 2008). The bar adds 130-200 mm to the overall length of the vehicle, whilst offering up to 180 mm of crush depth. This is split between 80 mm of EPP and up to 100 mm of space between the frame and front face of the vehicle. The results from testing at 30 km/h impact speeds showed the device could reduce the $HIC_{15}$ by up to 91% (from 696 to 66); the peak head accelerations by 64-68%, the cumulative 3 ms acceleration value for both the chest and Pelvis by up to 51%, the sternum deflection by up to 42% and the femur peak accelerations by up to 85%. Additionally, the 10-12 m VRU throw distance (the distance between pre and post VRU position) was similar to real world distances which showed the addition of a bar did not negatively influence post-primary impact kinematics.

Following on from work conducted during the APROSYS SP2 work package, Feist et al. (2009) analysed pedestrian head injuries caused by both the primary and secondary impact during simulated collisions with three different flat fronted vehicle designs. The findings of the simulations were also compared to data collected within the APOLLO database, which stores information on hospital discharge and includes cases where casualties received head injuries from collisions involving heavy vehicles.

Simulated collisions were carried out using vehicle geometries representing three different flat-fronted vehicle types; a long haul HGV, a short haul HGV and a bus (Feist *et al.*, 2009). Test parameters were varied for over 300 simulations including: ground clearance (model specific), vehicle speed (30-40 km/h), braking point (-1s before collision to +0.2s), pedestrian gait (10 postures), direction pedestrian is facing (±60°) and friction (HGV and VRU, shoe to ground and VRU to ground). The mean, median and quartile ($25^{th}$/$75^{th}$ percentile) values for the peak rotational/translational accelerations, head injury criterion (HIC), cumulative 3ms criterion (cum3ms), Gambit (Generalised Acceleration Model for Brain Injury Threshold) (G) and head impact power (HIP) results, for both the primary and secondary impacts, can be seen in Table 25.

**Table 25: Primary and secondary impact outcomes, table adapted from (Feist *et al.*, 2009)**

| Impact Phase | Value | Peak Head Acceleration (rad/s$^2$) | (g) | HIC | 3ms (g) | G | HIP (kW) |
|---|---|---|---|---|---|---|---|
| **Primary** | Mean | 9605 | 195 | 2999 | 136 | 0.82 | 90 |
| | 25$^{th}$ %ile | 5329 | 93 | 477 | 87 | 0.40 | 30 |
| | Median | 7848 | 156 | 1022 | 114 | 0.64 | 55 |
| | 75$^{th}$ %ile | 11616 | 225 | 2041 | 160 | 0.95 | 83 |
| **Secondary** | Mean | 69285 | 809 | 21013 | 398 | 3.82 | 444 |
| | 25th %ile | 44552 | 553 | 6850 | 284 | 2.75 | 240 |
| | Median | 66292 | 866 | 20527 | 434 | 4.10 | 406 |
| | 75th %ile | 91976 | 1026 | 29122 | 499 | 4.74 | 605 |

A breakdown of the primary impact injury values by vehicle type can be seen in Table 26. Interestingly, the pedestrians struck by the bus and long haul HGV had a lower injury risk, when compared to the short haul HGV, because they struck the low mounted windscreen and large fibre reinforced plastic grille. The head of pedestrian struck by the short haul HGV, however, struck the lowermost section of the much stiffer windscreen edge and sheet metal covering the front of the vehicle.

**Table 26: Median primary impact outcomes by vehicle type, table adapted from (Feist *et al.*, 2009)**

| Vehicle Type | Peak Head Acceleration (rad/s$^2$) | (g) | HIC | 3ms (g) | G | HIP (kW) |
|---|---|---|---|---|---|---|
| **All** | 7848 | 156 | 1022 | 114 | 0.64 | 55 |
| **Short Haul HGV** | 11919 | 216 | 1756 | 159 | 0.89 | 79 |
| **Long Haul HGV** | 6642 | 117 | 835 | 108 | 0.59 | 40 |
| **Bus** | 6452 | 92 | 577 | 8 | 0.40 | 31 |

A search of the APOLLO database located 104 HGV to pedestrian cases with 74 head injuries (Feist *et al.*, 2009). It was found that 21% of all head injuries analysed featured translational acceleration as a single injury mechanism, 69% for rotational acceleration and 10% featured both. The study concluded that secondary impacts are a frequent and major issue for VRUs, especially for those hit by a vehicle with a flat front end design, and that providing better primary impact protection is not enough on its own. Post-impact kinematics of the VRU must also be considered to mitigate the outcomes of the secondary impact and prevent the casualty from being struck by a nearby vehicle or roadside furniture.

Valladares et al. (2017) developed an energy absorbing frontal structure to improve the VRU crashworthiness of an electric heavy quadricycle (L7e category vehicle). The geometry of the nose was shaped to prevent the head of a Hybrid III 50th male dummy from striking the cabin (e.g. A-pillars) or windscreen (if positioned laterally centred in front of the vehicle) while still retaining an acceptable direct field of vision for the driver. The design also featured a rounded circular profile at the height likely to strike the VRUs legs to encourage deflection and reduce the risks of a run-over event. The nose was constructed out of composite materials to ensure an adequate balance between stiffness and being light enough to comply with the 1.2% of the mass of the vehicle (18 kg) mass limit for pedestrian frontal protection systems (including all brackets and fixings to the vehicle) specified by EC Directive 2005/66/EC (UNECE, 2005). The initial prototype had a thickness of 25 mm (20 mm polyvinyl chloride (PVC) foam core and 5 mm for layers of glass fibre resins and gelcoats) and had a total mass of 31.4 kg (Valladares *et al.*, 2017). A Finite Element (FE) model of the frontal structure was created and validated by correlating with experimental data taken from headform impact tests against the frontal structure.

Eight follow up design configurations were evaluated to understand if the crashworthiness of the frontal structure could be optimised. These included frontal structures with similar geometries, but a range of different composite material layer thicknesses and/or glass fibre resin densities. To test these optimised solutions, four impact scenarios, with locations and impact energies based on existing tests for pedestrian protection, were selected (Table 27).

**Table 27: Test configurations for each impact scenario, table adapted from (Valladares *et al.*, 2017)**

| Impact Scenario | Wrap Around Distance (mm) | Launch Angle (º) Towards Ground | Initial Velocity (m/s) | Impact Energy (J) |
|---|---|---|---|---|
| 1 (Lower Leg) | 625 | Horizontal | 9.08 | 825.51 |
| 2 (Upper Leg) | 1000 | 50 | 7.65 | 585.24 |
| 3 (Head) | 1500 | 65 | 5.43 | 295.70 |
| 4 (Head) | 1700 | 65 | 5.43 | 295.70 |

Out of the eight proposals, all were found to perform better than the prototype material for impact scenarios 1-3 (Valladares *et al.*, 2017). Overall, design configuration 4 was found to best optimise the energy absorbing properties of the frontal structures. This configuration minimised $HIC_{15}$ for a given mass, whilst maximising the energy absorption ratio. The study concluded that the use of composite materials, when used in combination with a rounded front end design and a significant ride down distance as afforded by the removal of the ICE engine block, can dramatically improve the VRU crashworthiness of L7e category vehicles (Valladares *et al.*, 2017).

Cao and Mo (2017) developed on a study conducted by Volvo Trucks which used MADYMO to test the relative safety performance of a pedestrian impact friendly HGV front end design when compared to a reference Volvo FH truck model. The enhanced front end structure was modelled on the Volvo FH with a 300 mm front end extension, with both vehicle front ends split in to seven separate structures. Each structure was assigned equivalent mass, spring and damper constants; however, the spring length was 300 mm longer for the HGV model with the enhanced front end design. A series of simulated collisions was then performed where a HGV, travelling at either 24km/h (6.67 m/s) or 40km/h (11.1 m/s), struck the side of a standing or walking (1.7 m/s) 50th percentile male model in six simulations for each HGV.

Finally, a verified FE model was used to investigate the impact protection performance of a frangible honeycomb structure contained within the front end extension. Six different honeycomb configurations were investigated, with five designs substituting the spring/damper properties of one structure out of the centremost five structures with that of the honeycomb structure and a final configuration replacing the spring/damper properties of all five structures with honeycomb structures.

A total of 14 head, neck and torso injury criteria were calculated for each simulation and compared between the reference Volvo FH model (Ref Truck) and Truck A (which modelled the spring-damper system) and Truck A with all six honeycomb configuration models (Trucks 1-6). For the six simulated collision scenarios calculated for the comparison between the Ref Truck and Truck A, injury criteria outcomes were improved for Truck A for a total of 83.3% of all recorded outcomes for the MADYMO model and 77.4% of all outcomes for the FE model. This shows that outcomes can be significantly improved for VRU to HGV collisions through the installation of a 300 mm energy absorbing layer into the front end structures of the cab.

When considering the honeycomb structure design, however, no further improvements in safety performance were consistently found over and above that already provided by the spring-damper system simulated by Truck A. At lower impact speeds (24 km/h) torso injury risks were found to increase relative to Truck A by up to 33%, whilst at higher impact speeds (40 km/h) head injury risks increased by 7.4%. Thus, while there are large gains to be made by introducing pedestrian protection structures, it is clear that a large number of interacting variables need to be considered in order to optimise the safety performance of the VRU crashworthiness structures.

Energy absorbing structures, such as the designs described above, partially solve the issue of increasing VRU impact protection; however, their impact on the operational capability of the vehicle (e.g. turning circle, direct vision performance) is important to also consider. The APROSYS Safety bar concept, developed by Feist and Faßbender (2008), and honeycomb structure proposed by Cao and Mo (2017) extend the front end between 130-300 mm from the front face of a HGV, whilst Robinson et al. (2010) proposed front end extensions of up to 2.25 m. Whilst these types of designs are suitable for distribution and long haul HGVs, due to their cab height, they may be less appropriate for Low Entry Cabs and buses, as they lack the large grille space below the windscreen to install a full body height system. This may therefore have a negative impact on the direct field of view of the driver.

Buses therefore have a unique issue in that much of the energy absorbing structure for VRU collisions is provided by the glazed areas of the bus front end, with the remainder absorbed by the bumper. Whilst the fracture mechanics of windscreens has been researched in depth, particularly for M1 passenger vehicles, there is currently no evidence base that evaluates the fracture mechanics of bus windscreens during impact loads. In particular, as the current generation of bus windscreens adopt a “wraparound” style, it is unknown how the radius of curvature of the windscreen affects outcomes. It is recommended that, to understand the effect that the glazed areas of the bus and their radius of curvature have on head injury risk, headform impact tests against the flat and wraparound areas of the windscreen glazing be performed.

## 5.4 VRU Run-Over Protection (VRP)

Published evidence defining the effectiveness of deployable run-over guards was not found by this literature review. It was therefore assumed that such systems would be capable of mitigating the severity of fatal and severe injuries by a single injury severity level in 90-100% of cases, whilst having no further effect on slight injury cases. Although this assumption was confirmed as realistic after discussion with Bombardier, the manufacturer of the Bodyguard inflatable run-over airbag for light transit rail trams, it is recommended that further research is performed to understand the technical feasibility and effectiveness when applied to buses. As this will require the development of new prototypes, it is recognised that such research may not be possible within the timeframe of this project.

## 5.5 Mirror Strikes (MST)

### *5.5.1 Class II Mirror Camera Monitor System (CMS) Replacement*

The requirements for replacing Class II mirrors with CMS would require the Class II mirrors to be removed and the installation of Class II CMS. This would prevent 90-100% of mirror strikes against roadside infrastructure and VRUs. Although CMS cameras will still protrude outboard from the edge of the bus, they may be located at a higher point on the bus, where VRU mirror strikes would be extremely unlikely, and will likely protrude <100 mm which, in turn, would prevent the majority of mirror strikes against roadside infrastructure. No further research should be required.

### *5.5.2 Energy absorbing mirrors*

Published evidence defining the effectiveness of energy absorbing mirrors was not found by this literature review. It was therefore assumed that such systems would have a similar effectiveness to that defined by the energy absorbing structures, whilst having no further effect on damage-only cases (as these would cause damage requiring replacement mirrors regardless). This assumption was confirmed as realistic after discussion with Ashtree Vision and Safety, a manufacturer of commercial vehicle mirror systems (including the knock-back mirrors); however, further research is recommended to better understand the effectiveness of such systems when applied to buses.

## 5.6 Summary of Solution Effectiveness Values

The previous sections reviewed the literature to determine the evidence base underpinning the effectiveness of proposed safety measure solutions for four secondary safety measures: Enhanced Front End Design (FED), VRU Impact Protection (VIP), VRU Run-Over Protection (VRP) and Mirror Strikes (MST). This state-of-the-art review found that high-quality research had only been performed for the FED and VIP safety measures. Each subsection reviews the range of research performed for each safety measure, with all subsections highlighting the current paucity in high-quality and relevant research relating to each proposed solution. All subsections, therefore, conclude that more relevant research is required to improve the evidence base that underpins the effectiveness values to be used for the proposed safety measure solutions. Finally, proposals for further research are put forward, with research for the FED and VIP safety measures highlighted as being the most important areas to consider.

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

# 6 Evaluation Testing

## 6.1 Introduction

The purpose of this section is to detail the research performed by this project to evaluate the effectiveness of the solutions associated with the Enhanced Front End Design (FED) and VRU Impact Protection (VIP) safety measure. Specifically, the following subsections evaluate the influence of the front end geometry on the likelihood of a VRU suffering a serious injury in case of a collision with the bus. The research described within these sections therefore provides the specific evidence base for establishing overall effectiveness values for the previously described VCW safety measure solutions.

## 6.2 Influence of Front End Geometry

As established in Section 5.2, there is currently a paucity of evidence specifically relating to the effectiveness of the design of bus front ends. While other industries have suggested that vertical raking and horizontal curvature improve outcomes when compared to flat fronted designs, this has not been specifically researched within the bus industry. Furthermore, to establish detailed geometric design principles that enhance bus front end safety, previous literature does not provide the level of detail that would be required to ensure such designs are optimised.

The aim of this research is to therefore investigate the influence of these geometric design parameters on the outcomes of collisions between bus front ends and VRUs. Specifically, this research aims, through computational simulations, to determine a combination of vertical raking and horizontal curvature front end design requirements that provide a reduction in head and thoracic injury risk during the primary impact and run-over risk when compared to current bus front end designs.

To achieve these aims, this research is split into three key Phases; Phase-1 which establishes baseline performance of current generation bus front end designs, Phase-2 which develops a parametric design of experiments (DOE) approach to optimise bus front end geometry reducing head injury risk of VRUs and Phase-3 which provides an easy to use bus front end design assessment tool based on comprehensive analyses for VRU’s risk of head injury, thoracic injury and run over incidents. Each Phase investigates the collision performance of bus front ends through the computational simulation of collisions between VRU and bus front ends. The following subsections therefore provide an overview of the methods adopted by these simulations and their outcomes.

### 6.2.1 Baseline Bus Design Performance (Phase-1)

The Phase-1 of the study evaluated the performance of the current generation bus front end geometry in terms of its likelihood to cause serious head injury to VRUs.

#### 6.2.1.1 Bus Model Design

*CAD Models*

Five CAD models were received from the BSS project partners, including a mix of double deck and single deck buses for both previous and current generation bus front end designs. Two CAD models were selected for use as baseline bus models, with these being a previous generation (B1) double deck bus model (with a box-shaped front end and A-pillars located on the frontal plane of the bus) and a current generation (B2) double deck bus model (with wraparound windscreens and A-pillars located rearward of the frontal plane of the bus).

The CAD models were used to define component designs, thicknesses and fixing points. Only the components at the front end of the bus were used in the simulations to make the model more computationally efficient, with no further modifications to their design. As the overall geometry of the bus front end is the most important variable in this research, the front end geometry of the baseline bus models were evaluated. This was performed at a number of key locations to define the approximate geometry of the bus front end Figure 12, including:

- **Windscreen rake angle:** at head height and on the bus longitudinal plane
- **Upper bumper rake angle:** at hip height and on the bus longitudinal plane
- **Lower bumper rake angle:** at knee height and on the bus longitudinal plane
- **Inboard horizontal angle:** at head height and 500 mm outboard from the bus longitudinal plane
- **Outboard horizontal angle:** at head height and 300 mm inboard from the corners of the front end of the bus

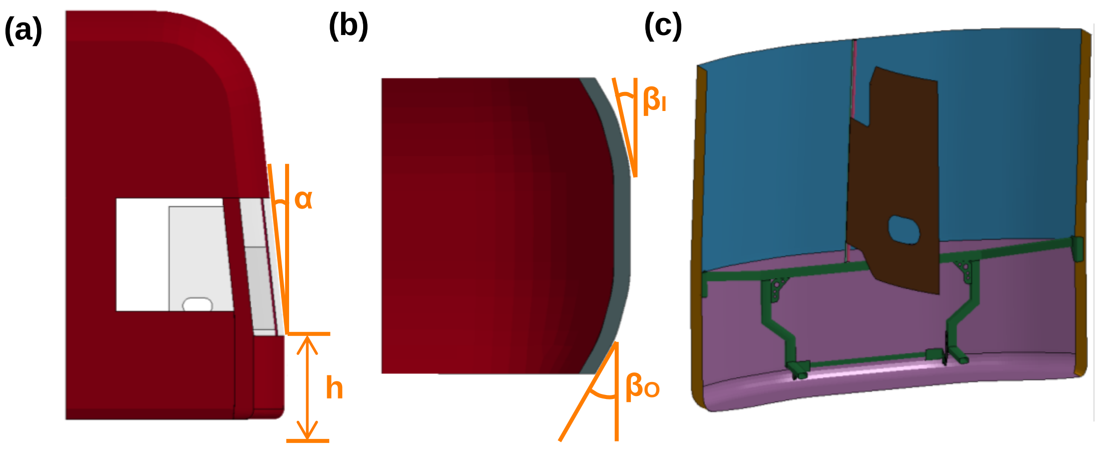



**Figure 12: Baseline geometry, chassis structure and bodywork design for proposed bus front end model from (a) side view, (b) plan view and (c) interior. Figure illustrates the vertical rake angle (α), inboard horizontal angle ($\beta_I$), outboard horizontal angle ($\beta_O$) and rake transition height (h).**

The bus front end geometry variables for previous generation model (B1) and current generation model (B2) were extracted as shown in Table 28.

**Table 28: Comparison of approximate vertical rake and horizontal angles at different locations for the previous and current generation bus models**

| Bus Model | Vertical Rake Angle | | | Horizontal Angle | |
|---|---|---|---|---|---|
| | Windscreen | U. Bumper | L. Bumper | Inboard | Outboard |
| **Previous Generation Baseline Model (B1)** | +6.5° | -2° | -11° | +4° | +8° |
| **Current Generation Baseline Model (B2)** | +11° | +1° | +1° | +7° | +21° |

*Bus Model Height*

The bus model height was defined as the maximum ride height of a vehicle from the ground plane in its unladen state. This was found to be same for both baseline bus models (B1 and B2), a height of 325 mm from the ground plane to the bus step.

*Bus Model Meshing*

Bus models were meshed within the LS_Dyna Finite Element Analysis (FEA) solver. Elements located within the impact region were assigned deformable properties, whilst rigid elements were used for all other regions where it was assumed the bus behaved as a rigid body. Average mesh size was set to 20 mm, whilst larger meshes were used for the rigid elements.

*Bus Model Materials*

Standardised material properties were used for consistency between different bus front end models. A list of the components and assigned material properties are reported in Table 29.

**Table 29: Materials used for bus front end models**

| Material | Material Properties | | | Key Components |
|---|---|---|---|---|
| | Density ($kg/m^3$) | Young's Modulus (MPa) | Yield Stress (MPa) | |
| **ABS Polymer** | 1,120 | 2,007 | 20 | Bumper |
| **Stainless Steel** | 7,740 | 200,000 | 280 | Chassis structure |
| **Glass Reinforced Plastic** | 1,720 | 5,500 | 100 | Windscreen frame |
| **Lexan Margard Polymer** | 1,200 | 2,350 | 60 | Driver assault screen |
| **Adhesive** | 1,000 | 500 | - | Join of Windscreen |

Windscreen Glazing:

As advanced windscreen FEA models remain computationally expensive, an objective of this research was to develop and validate a simpler, more computationally, efficient FEA model for use in the project. This was performed by benchmarking the kinematics of a headform impacting a previously validated glazing model that utilises a more complex material model and finer mesh resolution and tuning the material properties of a simpler glazing model that implement a coarser mesh and uses a simpler definition of the material properties.

During the benchmark simulation the headform was impacted at 20 mph (8.94 m/s) against a square test specimen of the windscreen glazing material which used a complex material model, solid mesh elements and a fine mesh resolution (2mm). These impact kinematics were replicated for the correlation simulation; however, in these simulations the glazing test specimen used a coarser (20 mm) shell element mesh with a less complex material model. The material properties (Young's Modulus, yield stress and failure criteria) of the glazing test specimen were then varied until adequate correlation was achieved with the benchmark windscreen glazing sample.

Good correlation between kinematic response of the complex and simplified models was observed Figure 13. Head injury criteria ($HIC_{15}$) values were overestimated by 13.8% by the simplified model, which, although a reasonable increase, also ensures that the worst-case scenario is modelled by the simplified windscreen glazing model.

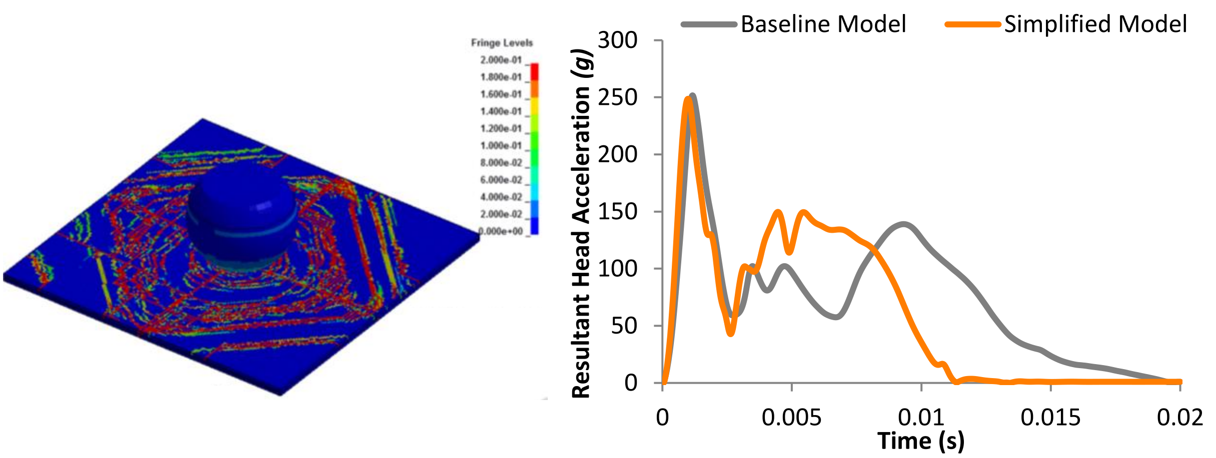



**Figure 13: Comparison of kinematics between baseline and simplified windscreen glazing models during simulated 20 mph headform impacts**

#### *6.2.1.2 VRU Models*

*VRU Model Design*

There are a wide range of human body models available for use in computational simulations varying significantly in both computational complexity and biofidelity. Advanced computational models, such as the Total Human Model for Safety (THUMS) (JSOL, 2019), are able to simulate the kinematics of the human body at the tissue level, whilst simpler multibody models, such as the MADYMO ellipsoid pedestrian model (TASS International, 2019), simulate the kinematics of segments of the human body at the macro level. There is often a trade-off between the availability (due to costs of licencing), computational efficiency and biofidelity of the models.

With consideration to the above factors, this study selected the LSTC Hybrid III FAST models for 50$^{th}$ percentile male and 5$^{th}$ percentile female for simulating VRU in the Phase-1 of this project (LSTC, 2019). The pelvis of these models was further adapted to simulate a standing posture.

*VRU Model Gait*

Both male and female VRU models were simulated with the right leg leading, at the point of maximum stride length Figure 14, travelling from the nearside to the offside of the bus on a trajectory parallel to the frontal plane of the bus.

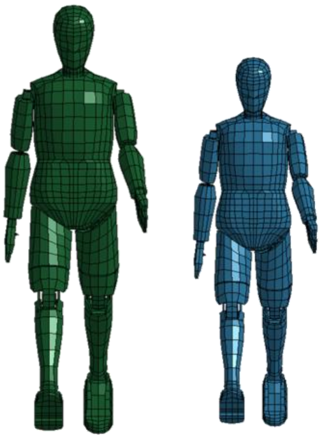


**Figure 14: VRU model gait for the fast 50$^{th}$ percentile male (left) and 5$^{th}$ percentile female (right) Hybrid III models**

#### *6.2.1.3 Simulation Set Up*

*Friction*

The ground plane was assumed to be a rigid concrete surface. A coefficient of friction of 0.6 was specified between the VRU models and the ground plane and a coefficient of friction of 0.3 was specified between the VRU models and all bus components.

*VRU to Bus Distance*

VRU models were positioned with 50 mm clearance between the model and the frontal plane of the bus prior to the commencement of the simulation.

*Initial Bus Velocity and Deceleration*

An initial bus velocity of 30 km/h and braking deceleration rate of 3 m/s$^2$ was set for the simulations.

*VRU Velocity*

An initial VRU velocity of 6 km/h was set for simulations.

*Impact points*

Five key VRU impact positions across the bus front end were identified based on a previous study (Edwards *et al*. (2018)). These impact positions (labelled 1-5) included two "outboard" impact positions (1 & 5 - 150 mm inboard from each edge), two "inboard" impact positions (2 & 4 - 725 mm outboard from the longitudinal plane of the bus), and one "central" impact position (3 - located on the longitudinal plane of the bus) illustrated in Figure 30.

Collisions in Phase-1 were simulated with VRU impacting the bus at impact points 1 and 3 only Figure 15.

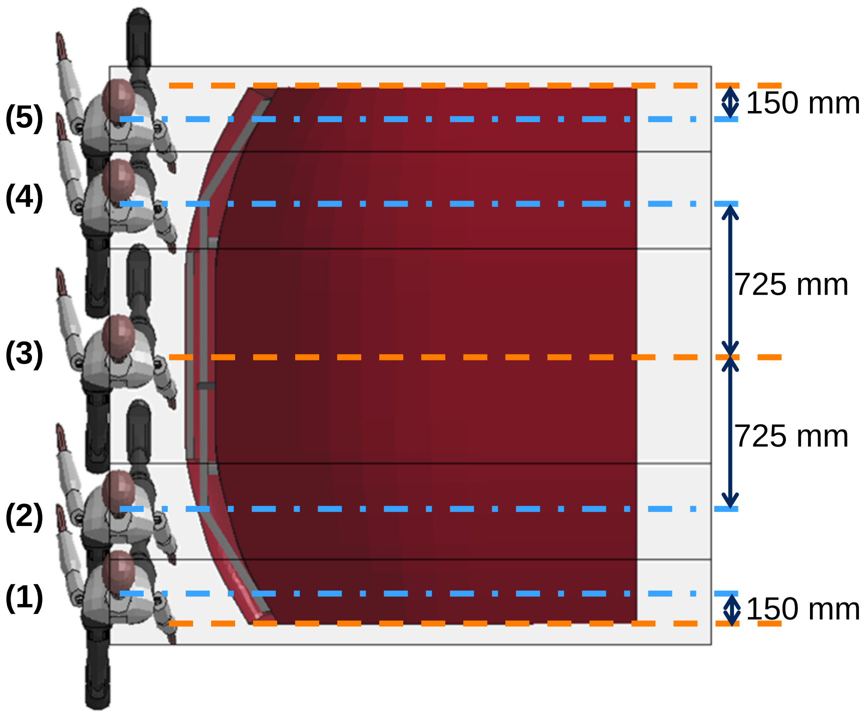



**Figure 15: VRU positioning at "outboard" (1/5), "inboard" (2/4) and "central" (3) impact points across front end of baseline proposed front end model**

### 6.2.1.4 Simulation Approach

*Performance of Previous and Current Generation Bus Design*

Eight different simulations were performed to establish the performance of the previous generation (B1) and the current generation (B2) of bus design. Two VRU dummies (LSTC Hybrid III "fast" 50th percentile male and 5th percentile female) and two different impact points (impact points 1 & 3) were evaluated for each bus design, whilst all other baseline properties and boundary conditions were kept constant.

*Analysis of Injury Risk*

The translational accelerations of the VRU head in the X/Y/Z axes were recorded during the primary impact, with the resultant head acceleration calculated from this data. Head injury criteria ($HIC_{15}$) values were then calculated for the primary impact during each simulation according to Equation 1 below:

$$HIC_{15} = \left\{ \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \right\}_{max}$$

$$where: a(t)\ is\ the\ resultant\ head\ acceleration\ and\ (t_2 - t_1) \leq 15\ \mathrm{ms}$$

(Equation 1)

Head injury risks were calculated from the recorded HIC values for the percentage risk of an AIS2+ head injury (equivalent to a serious head injury in STATS19 definition). The probability of AIS2+ head injury (i.e. head injury risk) was calculated according to the formula described by Mertz (1993) and replicated in Equation 2 below:

$$p(AIS2+) = \varphi\left(\frac{ln(HIC_{15}) - 6.96352}{0.84664}\right)$$

(Equation 2)

The vertical displacement of centre of gravity of the VRU was also recorded for 1.0 second after impact, with the peak vertical displacement recorded for each simulation. A run-over event was determined as a <1 mm peak vertical displacement of the centre of gravity of the VRU (based on this being associated with the VRU being impacted downwards and dragged under the bus).

### 6.2.1.5 Evaluation of Results

*Head Injury Risk*

Head injury risk outcomes showed the better performance for current generation (B2) over previous generation (B1) bus design for reducing head injury risk to VRU (Table 30). The results showed a 39% reduction in the average AIS2+ head injury risk across all investigated scenarios. The rationale behind this reduction in head injury risk is linked to the differences in geometries between the bus front ends (see Table 28), where the previous generation of bus front end had a much shallower rake angle and less horizontal curvature than the current generation of bus front ends.

Importantly, when considering the differences between two separate bus front end designs, it is clear that the wraparound design adopted by the current generation of bus front ends (B2) reduced the risk of a head injury. When impacting the front corner of the bus (impact point 1), it is clear that, on average, the current generation of bus front ends (B2) provides a 47% reduction in head injury risk. It is therefore recommended that bus front ends with a ≥150 mm radius of curvature wraparound windscreen be specified by the BSS.

**Table 30: Head impact criteria scores and AIS2+ head injury risks for simulated VRU collisions with the previous (B1) and current (B2) generation baseline bus models**

| Bus Model | VRU Dummy | Impact Point | $HIC_{15}$ Score | AIS2+ Head Injury Risk | Av. AIS2+ Head Injury Risk |
|---|---|---|---|---|---|
| B1 | 50th Percentile | 1 | 517 | 19.9% | 19.0% |
| | | 3 | 488 | 18.1% | |
| | 5th Percentile | 1 | 552 | 22.1% | 23.8% |
| | | 3 | 606 | 25.5% | |
| B2 | 50th Percentile | 1 | 349 | 9.5% | 12.1% |
| | | 3 | 434 | 14.6% | |
| | 5th Percentile | 1 | 406 | 12.9% | 14.1% |
| | | 3 | 444 | 15.3% | |

The head injury risk for the 5th percentile female was found to be higher than the 50th percentile male under all impact scenarios simulated, regardless of the bus front end design. On average there was a 25.6% increase in head injury risk for 5th percentile females (vs. 50th percentile males) associated with the previous generation of bus front ends (B1), whilst there was a 16.6% increase in head injury risk for the current generation of bus front ends (B2). Again, this is likely due to the differences in geometry at the relevant head height of each dummy, with less vertical raking of the windscreen present at the lower head height of the 5th percentile female.

*Run-Over Risk*

It was found that 7/8 (88%) collision simulations resulted in a run-over event. The one simulation that didn't result in a run-over event was the 50th percentile male impacting the nearside outboard position (1) of current generation (B2) bus design. It was observed that the vertical rake of the windscreen for the current generation of bus was greater at the edges of the windscreen than at the centre, so it was likely that the reduction in injury risk was caused by this increased vertical rake.

These results contrast with the accidentology data seen from pedestrian run-over collisions with buses, where around 33% of such fatalities were run over by buses (Edwards *et al.*, 2018). These differences are likely to be due to the biofidelity of the dummy and due to the method with which run-over risk was defined. With the stiff shoulder of the Hybrid III FAST thorax, the interactions with the bus front end may be unrealistically forcing the VRU model down towards the ground relative to real-world interactions. Furthermore, the use of the peak vertical displacement of the centre of gravity of the VRU over a 1 second simulation is only a simple metric for describing run-over risk as it does not account for lateral movement of the VRU.

### 6.2.2 Bus Front End Design Optimisation (Phase-2)

The Phase-1 of the study showed the better performance of current generation (B2) bus front end design in reducing the risk of serious head injury to VRU. The goal of Phase-2 was to improve upon the safety performance of current generation bus (B2) by modifying the geometrical parameters of bus front end using a design of experiment (DOE) approach.

#### 6.2.2.1 Bus Model Design

The general design philosophy adopted for the chassis, glazing and bodywork of the current generation (B2) bus front end was maintained for the optimised bus front end model. Limits for vertical raking and horizontal curvature were introduced with automatic adjustment to speed up the design of experiments process. This was achieved by adopting the basic shape of the structural chassis elements for the bumper and providing extra curvature to the bus front end by extending and angling the structural beams where necessary. Basic glazing and bodywork components were then modelled to recreate the curved and raked bus front end to be investigated during Phase-2. Component thicknesses and cross-sections were established based on equivalent components in the current generation (B2) of bus front end models (Figure 27 provides images of the baseline proposed bus front end).

Other elements of the bus model design, including the bus model height, meshing and material properties, were adopted from Phase-1 to remain consistent with the current generation (B2) bus front end design (see Section 6.2.1.1). This ensures that only the influence of the global geometric parameters on the safety performance of bus front end design are investigated.

#### 6.2.2.2 VRU Models

Phase-2 of the study investigated only the 50$^{th}$ percentile male LSTC Hybrid III FAST model. Exploration of different sized VRU models was considered out of scope for Phase-2 due to budget constraints. VRU gait and travel direction were both selected to remain consistent with the Phase-1 characteristics (see Section 6.2.1.2).

#### 6.2.2.3 Simulation Set Up

Phase-2 of the study investigated the effect of VRU velocity on bus front end safety performance. This was achieved by incorporating VRU velocities between 2 km/h to 8 km/h in increments of 2 km/h in the DOE process. Furthermore, Phase-2 of the study investigated the safety performance across the whole width of the bus front end by simulating VRU collision with the bus at all impact points (1 to 5) identified in Phase-1 of the study (Figure 30).

Other elements of the simulation set up, including friction settings, initial bus to VRU distances and bus velocities and decelerations, were adopted from Phase-1 to remain consistent with the current generation (B2) bus front end design (see Section 6.2.1.3).

#### 6.2.2.4 Design of Experiments (DOE) Approach

The design of experiments (DOE) approach consisted of six variables (Table 31). The inboard and outboard horizontal angles limits were set from 0° to +30° and +30° to +60° respectively in 5° increments. The vertical rake angle limits were set from -2° to +30° in increments of 2°. Vertical rake angle was applied across the entire bus front end. In total, 80 different collision scenarios between 50th percentile male VRU and bus front ends were simulated.

**Table 31: Summary of design of experiments variable ranges**

| Variable | Baseline | Range | Intervals |
|---|---|---|---|
| **Inboard Angle** | +15° | 0° to +30° | 5° |
| **Outboard Angle** | +30° | +30° to +60° | 5° |
| **Vertical Rake** | +6° | -2° to +30° | 2° |
| **Rake Transition Height (mm)** | +1,130 | +430 to +1,230 | 100 |
| **Impact Point (Figure 30)** | 1,3 | 1-5 | - |
| **VRU Velocity (m/s)** | 6 | 2 - 8 | 2 |

Head injury criteria ($HIC_{15}$) score, AIS2+ head injury risk, and run-over events were calculated for each simulation in Phase-2 following the same methods as in Phase-1 of the study.

#### 6.2.2.5 Evaluation of Results

*Head Injury Risk*

AIS2+ head injury risk of all 80 simulations were compared to the current generation (B2) bus front end design in order to establish the design parameters that would reduce the likelihood of head injury. This resulted in 25 design simulations (Compliant) having lower head injury risk than the current generation bus B2 while 55 designs simulations (Non-compliant) resulted in higher head injury risk than B2. The analyses of these design iterations concluded the minimum values of design parameters (P0) required for reducing head injury risk (Table 32). An average reduction of 34% in AIS2+ head injury risk as compared to B2 was achieved through design optimisation

**Table 32: Enhanced bus front end (P0) geometry design requirements**

| Variable | Baseline |
|---|---|
| **Inboard Angle** | +15° |
| **Outboard Angle** | +30° |
| **Vertical Rake** | +6° |
| **Rake Transition Height** | +800 mm |

*Run-over Risk*

When analysing the run-over risks for all 80 design simulations, 24% of compliant designs resulted in a run over event compared to 55% for non-compliant designs (Table 33).

**Table 33: Number of run-over events associated with the compliant and non-compliant bus front end designs**

| | Run-Over Event | |
|---|---|---|
| | Yes | No |
| **Compliant** | 6 | 19 |
| **Non-Compliant** | 30 | 25 |

### *6.2.3 Detailed Bus Front End Design Analysis (Phase-3)*

Phase-2 of the study showed the effect of different bus front end geometry parameters on the likelihood of head injury to VRU. This work suggested modifications (rake angle, horizontal angle, rake transition height) to the current generation (B2) of bus front end design, resulting in a reduction in head injury and run-over risk for VRU. However, Phase-2 had quite few limitations including lack of thoracic injury risk assessment, consideration of only a single VRU group (50$^{th}$ percentile male pedestrian) and single bus velocity (30km/hr) among other limitations. The goal of Phase-3 of this study was to perform a more detailed analysis while addressing the limitations of Phase-2 and develop an easy to use tool to assess the relative aggressivity of bus front end geometries regarding VRU injury protection.

#### *6.2.3.1 Bus Model*

A series of buses were modelled using the finite element analysis (FEA) package LS-DYNA. As well as the previous generation bus (B1), the current generation bus (B2) and the Phase-2 enhanced geometry bus (P0), a further enhanced design (Px) was derived in Phase-3 of this analysis. A similar approach was taken for all models, with the intention of reducing variability due to factors other than those under investigation, e.g. material choice or vehicle kinematics.

The following steps were taken in order to create computationally efficient, yet representative bus models:

- Only the front end (half way through the front axle) of the bus was modelled.
- Only the A-surfaces and intrusion regions were modelled as deformable.
- All other surfaces were modelled as rigid entities.
- A 20 mm average mesh size was used.
- A correlated glass material model was created for this project.
- The driver assault screen, bumper beam and cross bus beam were modelled.
- The mass of the bus was assumed to be 18 tonnes.

A consistent height of 325 mm from floor to bus step has been maintained across all simulations Figure 16. This ensures a worst-case test scenario (i.e. max tyre pressure, unladen bus).

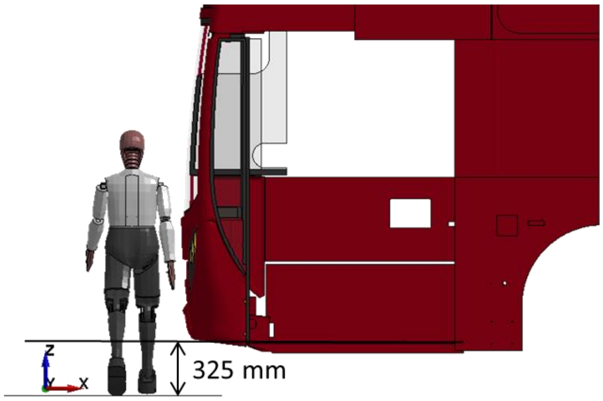



**Figure 16: A bus model illustrating the step height which was applied to all designs**

The models for the previous generation bus (B1) and current generation bus (B2) were created from production drawings provided by manufacturers. The P0 and Px models used in the design of experiments study are conceptual and as such, no complete bus assembly CAD exists for them. These models were created by taking the B2 bus mesh and morphing it onto the conceptual geometry. Structurally therefore these new concepts represent evolutions of the B2 structural designs. The conceptual models also retain many of the B2 feature lines, recesses and A surface depths Figure 17. These steps were taken to ensure that these conceptual models were as close as possible to potential future buses that might enter production. This is important since the deformation characteristics of the bus front play an important part in determining the likelihood of injury. However, it is acknowledged that these conceptual features may not be representative of all possible future bus designs.

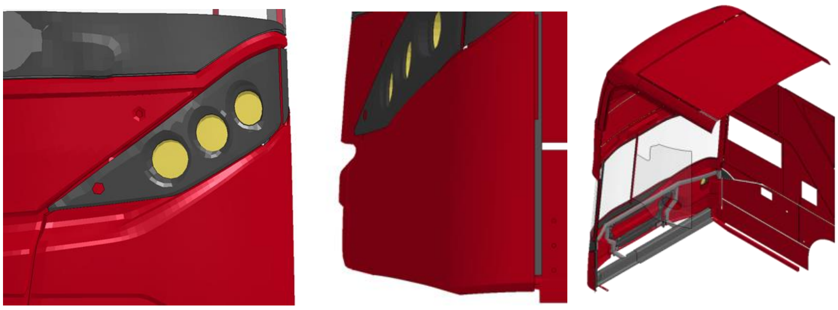


**Figure 17: Internal and external features retained from B2 in conceptual bus models**

*Windscreen Material Model*

The laminated safety glass used in windscreens is a composite structure constructed of a layer of clear polyvinyl butyral plastic (PVB) sandwiched between two layers of glass. The function of the PVB layer is to prevent the windscreen from breaking into large jagged pieces on impact and to retain some structural strength in the broken pane. The behaviour of the glass is an important factor in determining the frontal crashworthiness of a bus, because the manner in which the glass fails has a substantial effect on the forces imposed on the VRU and their subsequent trajectory. A more representative but efficient material model for the bus windscreen was developed in order to improve the accuracy of simulations in Phase-3, while balancing this with computational efficiency.

The windscreen material model from Phase-1 of the project was carried over and its properties tuned to correlate with test data from physical headform impact tests (see Section 6.3). The more computationally efficient shell windscreen model taken from the Phase-1 of the project was used as the starting point. A duplicate shell PVB layer was added to improve the netting effect and the properties of the two materials were tuned in a correlation exercise in order to develop a representative material model.

In order to obtain a benchmark response, and determine the behaviour of the windscreen during impact, an initial simulation was performed using a complex windscreen material model. This model used solid elements and a fine mesh resolution which was very computationally heavy (runtime 2.5hrs versus shell model of 11 minutes). The purpose of this pilot model was to determine the maximum resolution and accuracy available using an FEA model and thus, provide a baseline against which the performance of a less computationally intensive model could be measured.

A series of impact simulations were performed to collect a dataset that could be matched to previously completed physical impact tests. The simulation conditions were set up to match the physical headform test conditions performed in Section 6.3, impacting the same current generation bus front end with a UNECE Regulation 127 adult headform impactor travelling parallel to the longitudinal axis of the bus at 11.1m/s.

This solid model displayed headform kinematics that were very similar to the videos of physical testing. It also demonstrated the netting effect of the (PVB) interlayer as the glass shattered Figure 18. This modelling technique could be further improved, but was not pursued due to the runtime cost.

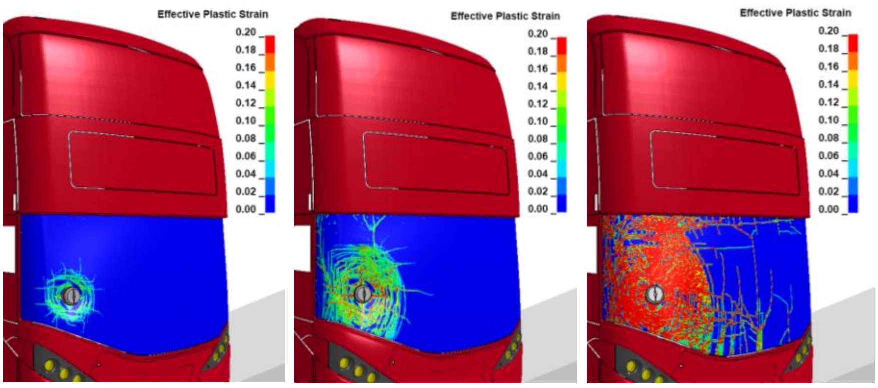



**Figure 18: Frames taken from a headform impact simulation showing the spreading failure pattern predicted by the laminated windscreen model**

The windscreen was correlated against test data in two impact positions; on the flat Figure 19 and the wraparound Figure 20 areas of the windscreen. Headform kinematics match that of the solid model and the videos of the test.

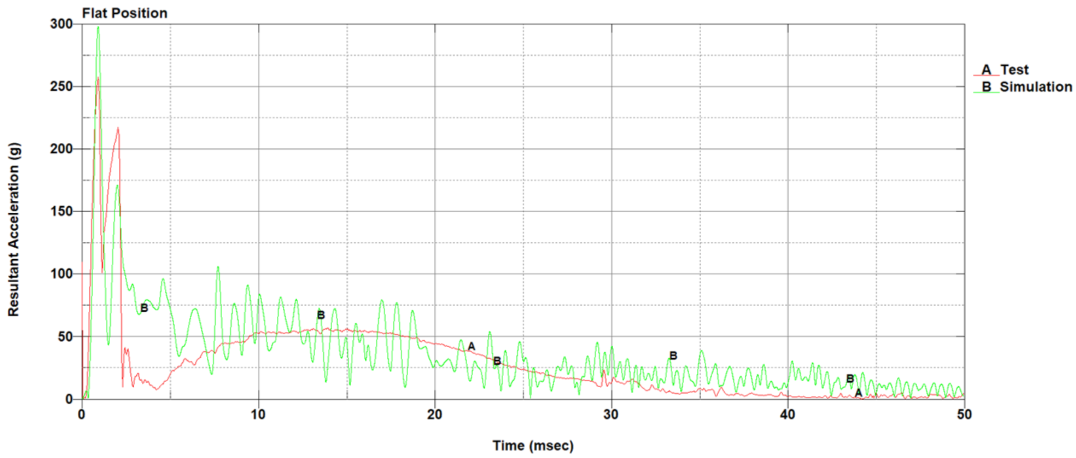



**Figure 19: An example of a correlation plot showing data from a simulation (green) and equivalent data from a physical test (red) collected in a test on the flat part of the windscreen**

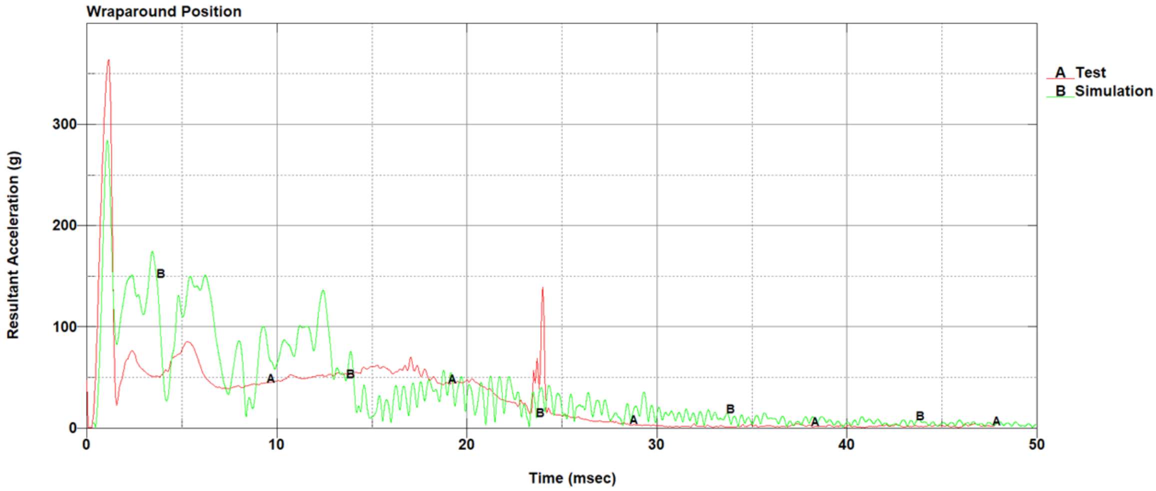



**Figure 20: An example of a correlation plot showing data from a simulation (green) and equivalent data from a physical test (red) collected in a test on the curved part of the windscreen**

### *6.2.3.2 Bus Speeds*

Simulated tests were run at bus impact speeds of 10, 20 and 30 mph. These speeds were found to be broadly representative of the most common speeds at which collisions between buses and VRUs occur in London.

#### 6.2.3.3 Impact Positions

Phase-3 of the study investigated the safety performance across the whole width of the bus front end by simulating VRU collision with the bus at all impact points (1 to 5) identified in Phase-1 of the study Figure 15.

#### 6.2.3.4 VRU Model

Three different VRU surrogates were investigated in Phase-3 of the study:

- 50$^{th}$ percentile male pedestrian
- 5$^{th}$ percentile female pedestrian
- 50$^{th}$ percentile male cyclist

These surrogates utilised simulated versions of existing crash test dummies. Existing crash test dummy models were used in preference to possible alternatives because:

- they have previously been validated in a range of collision scenarios,
- they are available in a range of sizes to represent different VRU groups,
- they are computationally efficient,
- and they are less costly.

*Choice of Crash Test Dummy*

Analysis of 43 injuries sustained in collisions between VRUs and buses in which the VRU was struck but not run-over showed that 44% of injuries were to the head and 56% were to the thorax (Edwards *et al.*, 2018). Phase-1 and Phase-2 of the project had solely concentrated on head injuries, but these data clearly indicated that thoracic injuries were, at least as, if not more important than head injuries.

Phase-2 was conducted using a 50$^{th}$ percentile male Hybrid III FAST crash test dummy. That dummy is not designed to measure forces acting on the thorax and is therefore unsuitable for measuring the effect of bus design on thoracic injuries. For this reason, the Hybrid III FAST dummy was replaced with a EuroSID-2re dummy in Phase-3. This dummy incorporates a more biofidelic torso with kinematics that are much more representative of a real human body when subject to side impacts. The dummy has three instrumented ‘ribs’ which permit intrusion into the thoracic cavity to be measured. Kuppa (2004) showed that maximum rib deflection was correlated with the probability of AIS3+ thoracic injuries in side impacts.

A pilot study was conducted to ensure that the EuroSID-2re would operate correctly in this test configuration and to understand the effect using this dummy would have on the severity of head injuries recorded.

Collisions were simulated at 10, 20 and 30 mph in positions 3 and 5 with B2. These collisions were repeated with both a Hybrid III dummy and a EuroSID-2re dummy to provide six directly comparable data sets.

Figure 21 shows the $HIC_{15}$ head injury severities measured with the Hybrid III and EuroSID-2re dummies. The figure shows that EuroSID-2re tends to reduce the $HIC_{15}$ score. The likely mechanism for this reduction is the greater lateral compliance of the EuroSID-2re torso, which tends to decrease the initial impact by absorbing some of the impact energy.

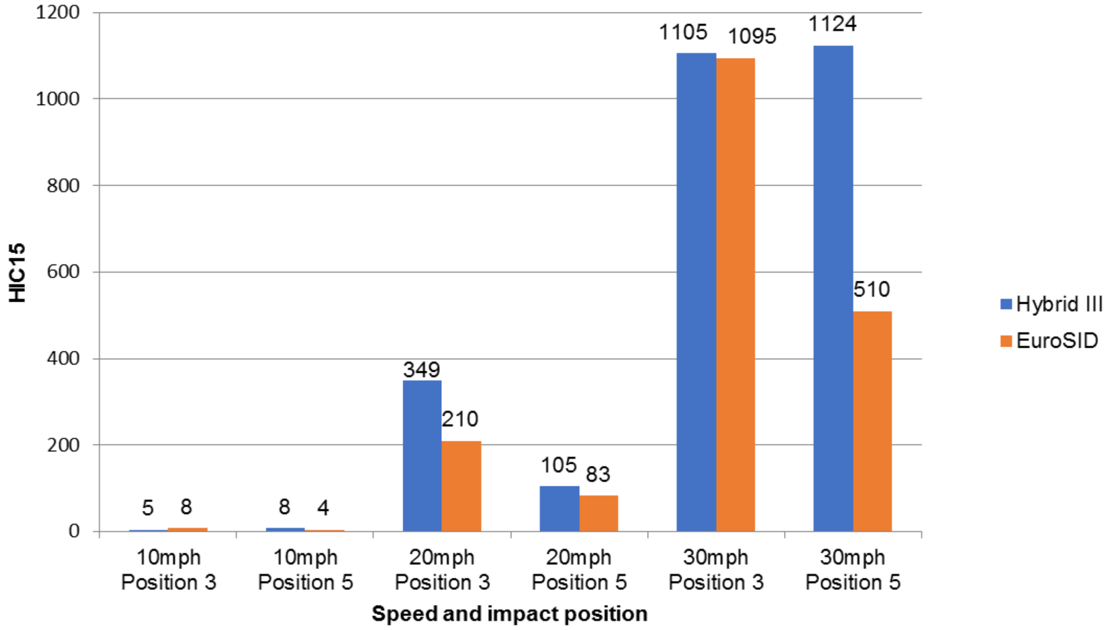



**Figure 21: Comparison of HIC15 head injury severities when measured using Hybrid III and EuroSID-2re dummies**

The results obtained in this pilot study indicated that EuroSID-2re would operate correctly in this collision configuration. The adoption of EuroSID-2re in place of the Hybrid III as the 50th percentile male pedestrian surrogate has allowed thoracic injury data to be collected and thus allowed frontal geometry to be further tuned to improve thoracic injury performance as well as head injury performance.

Unpublished Metropolitan Police fatal collision data collected between 2009 and 2014 and analysed by TRL shows that serious leg injuries have only been recorded in fatal bus collisions in which the VRU was run-over. This project sought to quantify the probability of a VRU being run-over having been struck by a bus but did not set out to predict the injuries resulting from run-over collisions. Therefore, the ability to accurately measure leg injury criteria was deemed unnecessary.

*Injury risk assessment*

Use of EuroSID-2re VRU model made it possible to assess the likelihood of head injury, thoracic injury and run-over events.

The rib deflection in EuroSID-2re dummy is correlated with the probability of AIS3+ thoracic injuries. So AIS3+ probabilities were calculated for both head and thoracic injuries to permit comparison. Run-over was treated as a binary (run-over/not run-over) metric. The injuries resulting from run-over events have not been well studied, however, given the mechanism of run-over events the resulting injuries were assumed to have a severity at least equivalent to AIS3+.

### Head Injuries

The risk resulting from head injuries associated with the collisions were calculated in two parts; first a $HIC_{15}$ calculation was performed, then the probability of injury at a certain AIS level was calculated as follows.

$$HIC15 = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} (t_2 - t_1)$$

*Where:*

*a(t) is the resultant head acceleration and (t2 – t1)≤15miliseconds*

$$p(head\ injury) = \varphi\left(\frac{\ln(HIC_{15}) - \mu}{\sigma}\right)$$

*Where:*

*φ is the cumulative normal distribution*

*μ=6.96352 and σ=0.84664 for AIS2+ head injuries,*

*μ=7.45231 and σ=0.73998 for AIS3+ head injuries,*

*μ=7.65605 and σ=0.60580 for AIS4+ head injuries*

### Thoracic Injuries

Thoracic injuries were calculated using the maximum rib deflection method specified by Kuppa (2004), in which an AIS value is calculated from the maximum thoracic rib deflection measured in the VRU model.

$$p(AIS3+) = \frac{1}{1 + e^{(2.0975 - 0.0482 \times \max rib\ deflection)}}$$

It should be noted that the EuroSID-2re dummy only has three ribs; lower, middle and upper. The risk of thoracic injuries was only calculated for the 50$^{th}$ percentile male pedestrian, as rib deflection in 5$^{th}$ percentile female dummy is not measurable.

### Run-over Risk

Simulations were run for 250 milliseconds in order to capture the initial impact, so the bus and VRU were still in motion at the point where the simulation stopped. If the whole sequence were simulated until both the VRU and bus had come to rest this would take a long time to compute and was unnecessary because it could be estimated.

The risk of being run-over by the bus was calculated by extrapolating the trajectory of the VRU at the end of the simulation to the point in time where the bus had come to a halt. The bus was assumed to start decelerating at the point of impact at a rate of 3.5m/s$^2$, which represents a realistic maximum deceleration that might be achieved by a human driver or Autonomous Emergency Braking (AEB) system. Run-over was assumed to be a binary condition in which the perimeter of the bus overlapped with a circle of 0.5m diameter centred on the dummy's Centre of Gravity (CofG). This allowed for the possibility of one of the dummy's extremities being run over and still passing the test, or the bus stopping before the wheels ran over the dummy, but still failing the test. Given the uncertainty inherent in this calculation and the potential for interaction with other vehicles or road features, this was felt to be a reasonable compromise. A limit of 1.5m from the side of the bus (Figure 22) was set on the lateral displacement of the dummy to account for the risk of a VRU being swept with excessive force into a roadside feature, e.g. a bus shelter or lamp column.

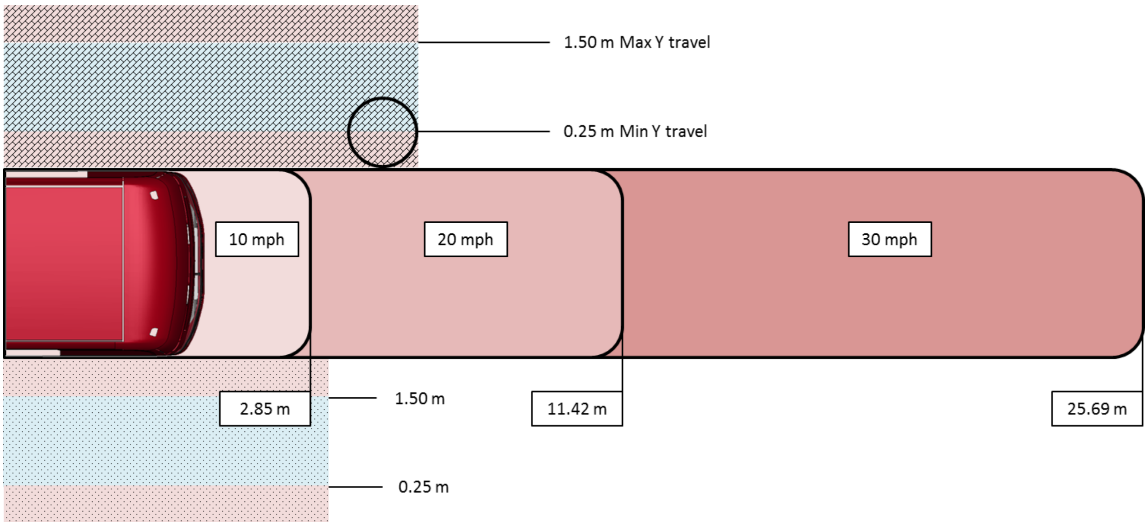



**Figure 22: Criteria for the estimation of VRU run-over Choice of VRU Gait**

### *VRU Gait*

Previous studies have shown that gait can affect the outcome of pedestrian collisions. In particular, the point in the gait cycle at which the collision occurs can affect head impact velocities. A pilot study was conducted to identify whether leading with the left or right foot would affect the severity of head and thoracic injuries recorded and whether the choice of leading foot would skew the results.

Collisions were simulated:

- at 10, 20 and 30mph (the average incident speeds),
- in impact positions 3 (centre) and 5 (offside),
- with B1 (previous generation) and P0 (Phase-2 enhanced geometry bus),
- with a gait cycle that started with the left and right foot,
- and with both the head injury criterion ($HIC_{15}$) and the thoracic rib deflection measured.

Figure 23 shows the effect of gait on $HIC_{15}$ for the EuroSID-2re dummy in collisions with B1 and P0 at 10, 20 and 30 mph in positions 3 and 5. The figure shows that gait does affect $HIC_{15}$, but the effect is not consistent, i.e. it can't be said that leading with one foot always leads to higher $HIC_{15}$ scores than leading with the other. For example, for B1 position 5 we can compare the green and purple bars for left and right leading foot respectively. At 10 and 20 mph the right foot shows a greater $HIC_{15}$ value, but at 30 mph the left foot value is greater. It is also clear that the effects of speed, impact position and bus design are much larger than those associated with gait change.

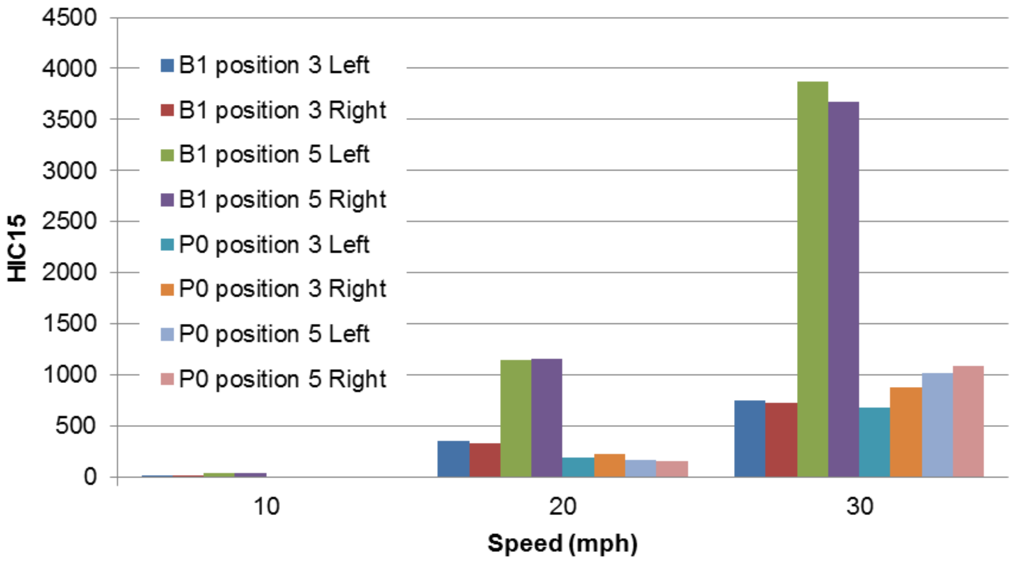



**Figure 23: The effect of gait on head injury criterion (HIC15) scores in collisions with B1 and P0**

Figure 24 shows the effect of gait change on rib deflection. It shows that gait change does affect rib defection, but the magnitude of that effect is much smaller than the effect of speed, impact position or bus design.

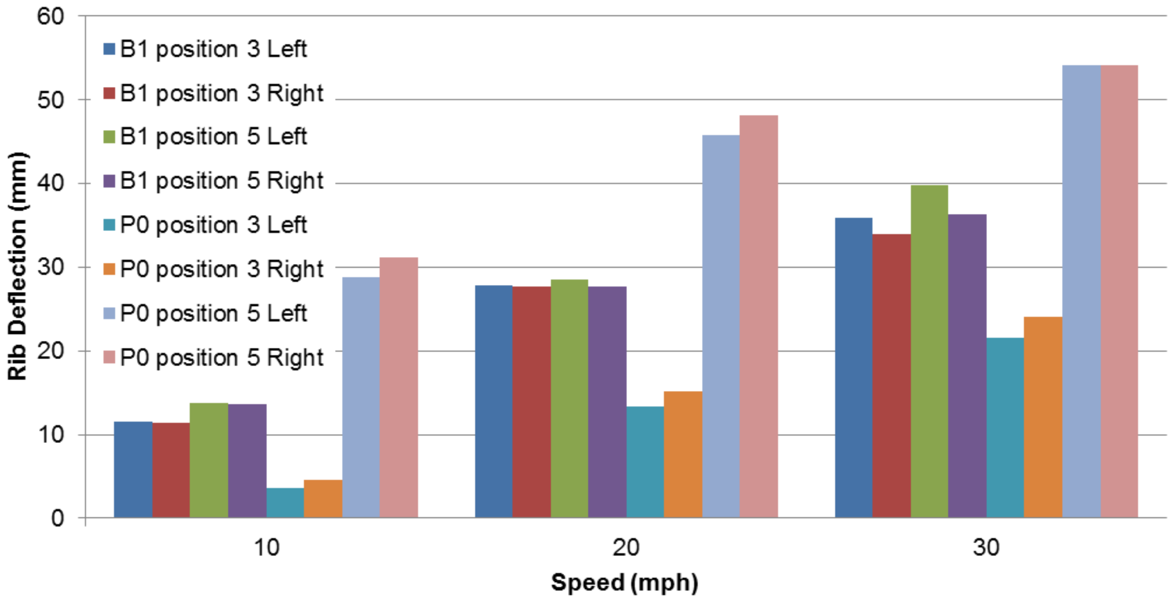



**Figure 24: The effect of gait on rib deflection in collisions with B1 and P0**

The results of the pilot study indicated that gait does not have a consistent effect on either $HIC_{15}$ or rib deflection. On average there was no difference in rib deflection, however the simulations in which the right foot was forward had on average a slightly higher $HIC_{15}$ value. Thus, all further simulations were conducted with the right foot leading as this represented the worst case.

### *Crossing Direction*

Analyses of collisions between VRUs and buses have shown collisions to occur far more often when the VRU is crossing from the nearside (56%) than the offside (17%). So, collisions were simulated with the VRU crossing from the nearside of the bus to the offside.

The crossing direction has an effect for two reasons; firstly, because the VRU is moving forward, the direction of their impact with the bus is tangential rather than being directly perpendicular to their direction of travel; and secondly the kinematics of the VRU's movement and their physiology means that an impact toward the outer edges of the bus will have a different effect depending on the direction that they are facing. However, it can be said that, unless the design of the bus is substantially asymmetrical, an impact in position 1, when crossing from the nearside, may be assumed to be equivalent to an impact in position 5 when crossing from the offside.

### *VRU Speed*

The VRU was simulated travelling perpendicular to the direction of travel of the bus, as if crossing the road, at 4kph for all simulations.

*Cyclist Model*

A computationally efficient bicycle model was created for this study (mass = 14.2 kg) using a mix of beam and shell elements. The cyclist surrogate was a $50^{th}$ percentile male Hybrid III dummy. The Hybrid III was chosen for these tests because, being more computationally efficient than the EuroSID-2re, it was more economical to simulate.

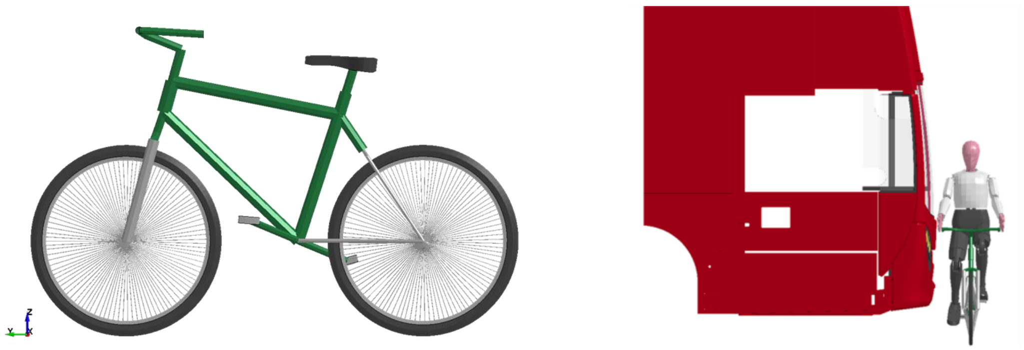


**Figure 25: The setup used for the simulation of bus versus cyclist collisions; bicycle model (left), bicycle with seated dummy in front of bus (right)**

### *6.2.3.5 Design of Experiments (DOE) approach for optimising bus designs*

The purpose of the DOE study was to find the combination of geometric parameters, which, on average, gave the best performance for all injury types at all speeds and impact positions. The complication here is that the geometric parameters may interact with one-another, e.g. changing the lower boundary height might change the effect of rake angle. Those geometric parameters might also interact with the impact position and the speed of the bus. There is also a possibility that a geometric change that improves head injury performance might make thoracic injury performance or run-over risk worse. Thus, the design that gives the best performance for one type of injury at one position and speed might give the worst performance for all other positions and speeds. A full investigation was needed.

The design of experiments study was undertaken in order to fully assess the combined effects of front-end geometry and collision speed. This study was designed to show how combinations of vertical rake, lower boundary height and horizontal curvature might interact with the speed of the bus and the point of impact.

The study was conducted in two phases using a series of simulated bus designs, which varied the geometry of the bus front end and vehicle velocity within set limits. In the first phase of the DOE study the limits used were those given in Table 34. The DOE performed in this first stage was a coarser analysis that was used to establish where the boundary of the design limits lie at a single impact speed (20 mph). This was taken as the boundary at which the performance of the modelled bus front end geometry no longer provides, on average, any additional benefit when compared to the current bus front end design (B2).

These design limits (Table 35) were subsequently used in the second phase of this study in a more detailed analysis to establish the relationship between injury risk and bus front end geometry within these boundary conditions. The LS-DYNA software automatically generated candidate designs within the prescribed geometric limits and tested their performance in collisions with a simulated 50th percentile male EuroSID-2re dummy who was crossing the road on foot from the nearside to the offside.

The injury risk metrics described earlier were used to evaluate the performance of each design. The output of the design of experiments study was a series of multi-dimensional response surfaces (Figure 26) representing the performance of each design at each impact position.

**Table 34: Design limits used for the first phase of the design of experiments study**

| | Minimum | Maximum |
|---|---|---|
| **Inboard Angle** | 10° | 30° |
| **Outboard Angle** | 25° | 45° |
| **Lower Boundary Height** | 600mm | 1000mm |
| **Rake Angle** | 2° | 30° |
| **Vehicle Velocity** | 20mph | |

**Table 35: Design limits used for the second phase of the design of experiments study**

| | Minimum | Maximum |
|---|---|---|
| **Inboard Angle** | 11° | 18° |
| **Outboard Angle** | 20° | 33° |
| **Lower Boundary Height** | 750mm | 978mm |
| **Rake Angle** | 4° | 23° |
| **Vehicle Velocity** | 8mph | 32mph |

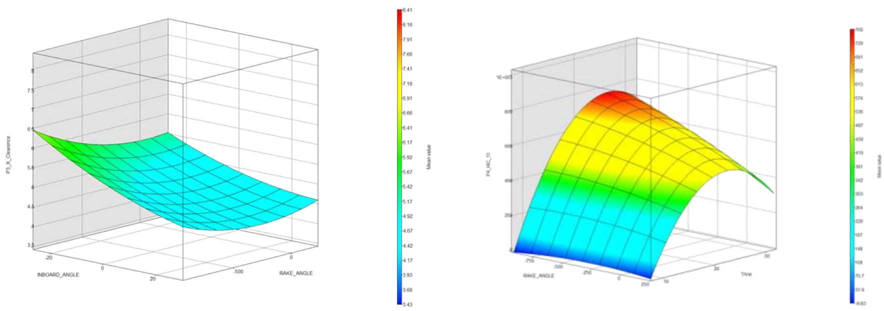


**Figure 26: Examples of response surfaces generated by the DOE study showing how the geometric parameters of the design may interact**

### *Generating an Enhanced Bus Front End Design*

An optimisation process was used to find the bus front end geometry (Px) that gave the best average performance across all three injury metrics, five impact positions and three impact speeds. The performance of potential solutions was weighted by impact speed to reflect the distribution of fatal bus collisions taken from Edwards *et al*. (2018), i.e. solutions giving superior performance at 20mph were weighted more heavily than those that gave better performance at 10 or 30mph due to the greater proportion of collisions at this speed. Ultimately it was found that weighting solutions toward 20 and 30mph gave superior results to those in which performance at 10mph was also considered. Thus the final specification for Px was derived by applying a 60% weighting to performance at 20mph and 40% to performance at 30mph.

The final specification for the geometry of Px is given in Table 36.

**Table 36: Enhanced bus front end design (Px) geometry**

| Inboard Angle | Lower Boundary Height | Outboard Angle | Rake Angle |
|---|---|---|---|
| 16.28° | 752.58mm | 24.7° | 7.24° |

### *Bus Front End Assessment Tool*

The results of the design of experiments study were used to create an assessment tool for bus front end. This Microsoft Excel based tool (Figure 27) allows the frontal geometry of a design to be quickly and easily assessed for its performance against target head injury, thoracic injury and run-over risks based on the performance of current bus front end designs (B2). This will provide valuable insight in the design stages for the bus manufacturers who are trying to balance the needs of the BSS geometric requirements with other aspects of the BSS and the needs of operators.

**Front End Geometry Performance Evaluation Tool**

**Inputs**

| | Horizontal Angle (°) | | | | |
|---|---|---|---|---|---|
| | **P1** | **P2** | | **P4** | **P5** |
| Minimum Boundary | 20 | 11 | | 11 | 20 |
| Maximum Boundary | 33 | 18 | | 18 | 33 |
| | | | | | |
| Test Point 1 | 20.00 | 11.00 | | 11.00 | 20.00 |
| Test Point 2 | 20.00 | 11.00 | | 11.00 | 20.00 |
| Test Point 3 | 20.00 | 11.00 | | 11.00 | 20.00 |

| | Rake Angle (°) | | | | |
|---|---|---|---|---|---|
| | **P1** | **P2** | **P3** | **P4** | **P5** |
| Minimum Boundary | 4 | 4 | 4 | 4 | 4 |
| Maximum Boundary | 23 | 23 | 23 | 23 | 23 |
| | | | | | |
| Test Point 1 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| Test Point 2 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| Test Point 3 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |

**Definitions:**

**Horizontal Angle:** Angle measured at each test point between the frontal plane of the bus and the tangent to the bus front end structures in a plane parallel to the horizontal plane.

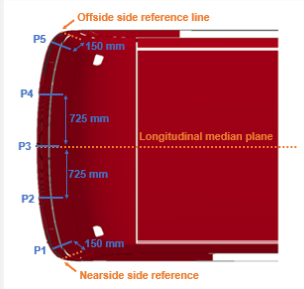
**Rake Angle:** Angle measured at each test point between the frontal plane of the bus and the tangent to the bus front end structures in a plane parallel to the median longitudinal plane.

**P1:** Outboard nearside test position, with test points located 150mm inboard from the nearside side reference line of the bus.

**P2:** Inboard nearside test position, with test points located 725mm outboard from the median longitudinal plane of the bus towards the nearside.

**P3:** Central test position, with test points located on the median longitudinal plane of the bus.

**P4:** Inboard offside test position, with test points located 725mm outboard from the median longitudinal plane of the bus towards the offside.




**Front End Geometry Performance Evaluation Tool**

**Outputs**

| | | Estimated Injury Risk of Current Bus Front End | | | Predicted Change in Bus Front End Injury Risk | | | Safety Performance Criteria Scores | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Speed** | **Test Position** | **HIC (%)** | **Rib Deflection (%)** | **Run-Over Proximity (m)** | **HIC (%)** | **Rib Deflection (%)** | **Run-Over Proximity (m)** | **HIC** | **Rib Deflection (mm)** | **Run-Over Proximity (m)** |
| **10mph** | P1 | 0.0% | 14.6% | 1.81 | ±5% | 10.6% | 0.78 | 1 | 0 | 1 |
| | P2 | 0.0% | 13.6% | 2.48 | 20.8% | ±5% | -0.45 | 0 | 1 | 2 |
| | P3 | 0.0% | 13.0% | 4.37 | ±5% | ±5% | -1.28 | 1 | 1 | 2 |
| | P4 | 0.0% | 13.2% | 2.29 | ±5% | ±5% | 0.66 | 1 | 1 | 1 |
| | P5 | 0.0% | 54.2% | 1.50 | ±5% | -43.2% | -1.11 | 1 | 2 | 0 |
| **20mph** | P1 | 2.9% | 36.7% | 0.50 | ±5% | ±5% | 0.51 | 1 | 1 | 1 |
| | P2 | 1.4% | 20.4% | 0.75 | 22.1% | -7.8% | -0.45 | 0 | 2 | 0 |
| | P3 | 5.1% | 22.1% | 2.81 | ±5% | -7.4% | -1.16 | 1 | 2 | 2 |
| | P4 | 8.4% | 18.3% | 1.47 | -8.4% | ±5% | 1.11 | 2 | 1 | 1 |
| | P5 | 6.9% | 58.4% | 1.79 | -6.9% | -37.2% | -0.91 | 2 | 2 | 2 |
| **30mph** | P1 | 32.7% | 59.8% | 0.87 | -6.6% | -7.6% | ±0.25 | 2 | 2 | 1 |
| | P2 | 30.8% | 31.1% | 1.25 | 5.1% | -10.0% | -0.44 | 0 | 2 | 2 |
| | P3 | 39.1% | 32.4% | 0.79 | -15.4% | -9.3% | -1.03 | 2 | 2 | 0 |
| | P4 | 14.3% | 29.2% | 1.49 | -13.7% | 8.2% | 1.55 | 2 | 0 | 1 |
| | P5 | 48.2% | 63.0% | 1.67 | ±5% | -26.2% | -0.71 | 1 | 2 | 2 |

| | |
|---|---|
| Weighted Front End Geometry Score | 26.7% |
| Safety Performance Criteria Scores with a Value of 0 | 8 |
| Front End Geometry Envelope Compliance | PASS |
| Bus Front End Geometry Star Rating | 3 |

**Interpretation of Safety Performance Criteria Scoring**

**Head injury Risk Criteria ( *HIC* )**
Scores of 0: Significant increase in head injury risk
Scores of 1: Negligible change in head injury risk (<5% change)
Scores of 2: Significant reduction in head injury risk

**Thoracic Injury Risk Criteria ( *Rib Deflection* )**
Scores of 0: Significant increase in thoracic injury risk
Scores of 1: Negligible change in thoracic injury risk (<5% change)
Scores of 2: Significant reduction in thoracic injury risk

**Run-Over Risk Criteria ( *Run-Over Proximity* )**
Scores of 0: Significant increase in run-over risk
Scores of 1: No change in run-over risk, with either an increase or neglible change in throw distance
Scores of 2: No change in run-over risk, with a significant reduction in throw distance (>0.25m reduction)

**Weighted Front End Geometry Score**
Sum of all scores weighted by bus impact speed and VRU impact position based on collision data (Edwards *et al*. 2018)
A weighted front end geometry score of 0% is considered equivalent to current bus front end designs

**Safety Performance Criteria Scores with a Value of 0**
Count of all safety performance criteria scores with a value of 0

**Front End Geometry Envelope Compliance**
Check that all horizontal and vertical rake angles are compliant with the front end geometry envelope requirements

**Bus Front End Geometry Star Rating**
Star rating score (0-5) based on weighted front end geometry score

**Figure 27: Bus front assessment tool interface**

#### *6.2.3.6 Bus Front End Performance Comparison*

Simulations were undertaken to compare the performance of:

- the previous generation bus (B1),
- the current generation bus (B2),
- the baseline proposed bus geometry defined in Phase-2 (P0), and
- the enhanced proposed bus geometry defined in Phase-3 (Px).

When involved in collisions with:

- 50$^{th}$ percentile male pedestrians,
- 5$^{th}$ percentile female pedestrians, and
- 50$^{th}$ percentile male cyclists.

*Method*

Collisions were simulated between the VRU and each bus at 10, 20 and 30mph. The VRU crossed from the nearside, leading with their right leg, at a speed of 4kph. Each simulation was set to run for 250ms, starting from a point at which the VRU was 50mm from the front of the bus. Each bus was pitched forwards by 2° as if it was braking heavily, although the speed of the bus was actually constant. For the 50$^{th}$ percentile male pedestrian, collisions were simulated at all three speeds and at all five impact points for all buses, giving a total of sixty simulations. For the 5$^{th}$ percentile female and 50$^{th}$ percentile male cyclist simulations were run for the scenarios shown in Table 37, giving a total of 32 simulations for each.

**Table 37: Collision scenarios simulated for the 5$^{th}$ percentile female pedestrian and the 50$^{th}$ percentile male cyclists**

| Vehicle Speed | Impact Position |
|---|---|
| **10** | 3 |
| **10** | 4 |
| **20** | 1 |
| **20** | 4 |
| **20** | 5 |
| **30** | 1 |
| **30** | 2 |
| **30** | 3 |

*Results*

Figure 28 shows the mean AIS3+ values resulting from thoracic and head injuries for all four bus designs for the 50$^{th}$ percentile male pedestrian. The values given are the mean of all impact positions at all speeds. The figure shows that the probability of an AIS3+ injury is considerably higher for thoracic injuries than head injuries for all four bus designs. The figure also shows a progressive improvement from B1 to Px for both thoracic and head injury performance.

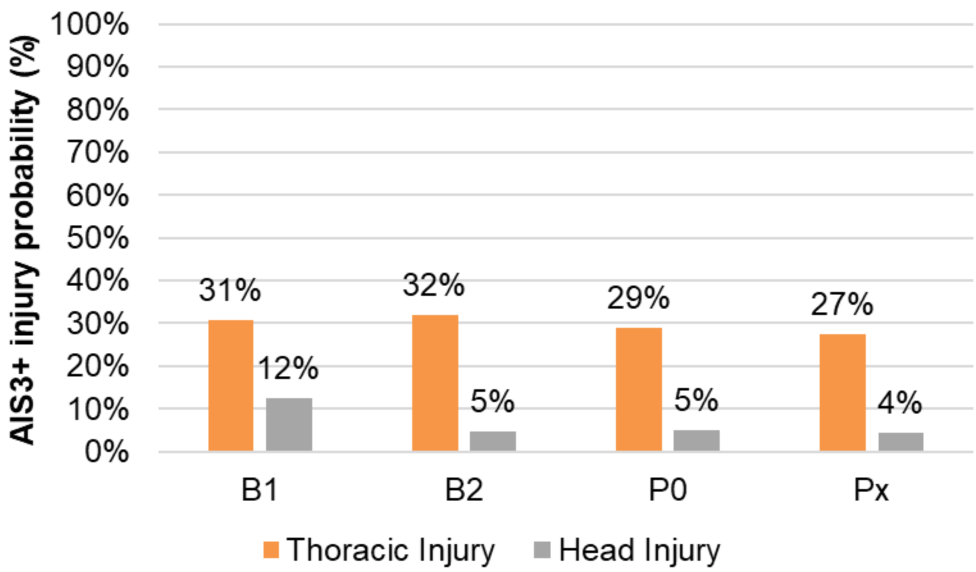



**Figure 28: Mean AIS3+ injury probability resulting from thoracic and head injuries for the 50th percentile male pedestrian**

Figure 29 shows the highest individual probability of an AIS3+ head and thoracic injury for each bus at every speed and impact location. This figure indicates that, while on average the probability of an AIS3+ injury progressively reduces as bus designs progress, the random nature of collisions mean that an individual collision scenario may be especially dangerous even when the bus design is on average safer.

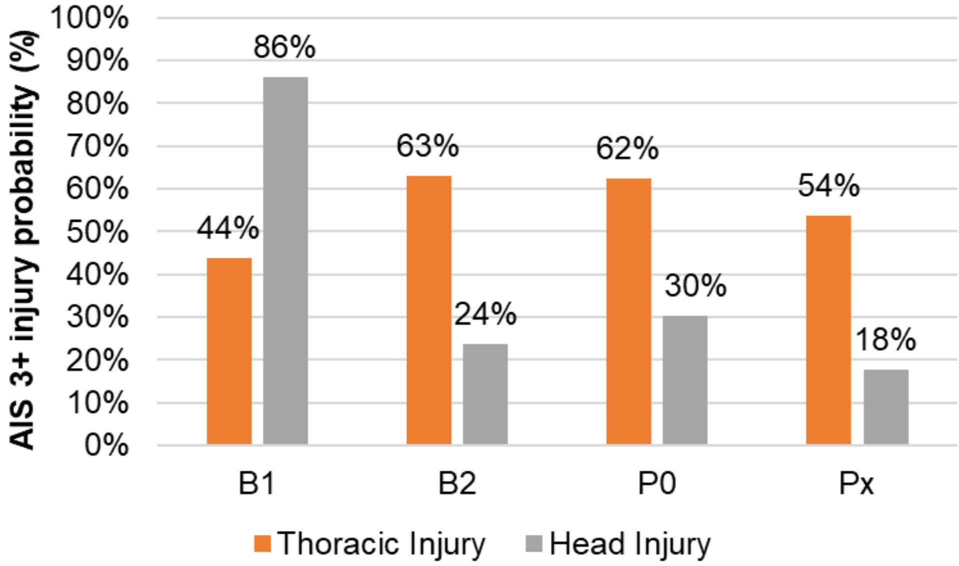



**Figure 29: Maximum individual injury for each bus at all impact positions and speeds for the 50th percentile male pedestrian**

Figure 30 shows the mean AIS3+ probability for head injuries for all collision speeds and positions for each VRU group and all bus designs. The figure indicates that P0 and Px both improve on the performance of B1. However, for the 50th percentile male cyclist, Px is no better than B2 and actually has a worse performance than P0. For the 5th percentile female pedestrian Px has a much better performance on average than B1 and a slightly better performance than B2. However, Px has a slightly worse performance than P0.

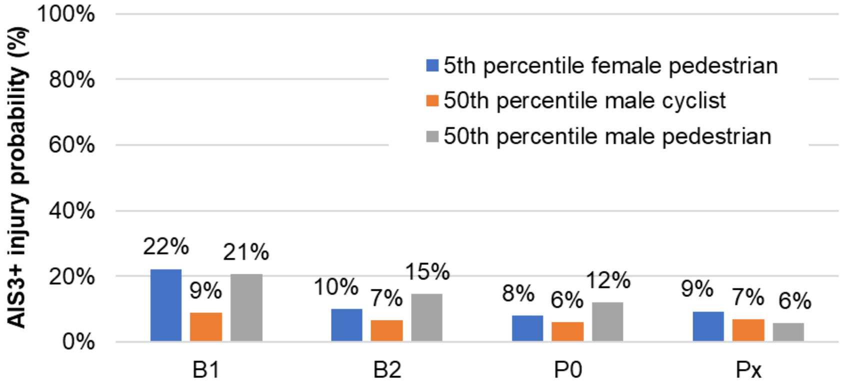



**Figure 30: Mean AIS3+ probability for head injuries for all collision positions and speeds for each VRU group**

Figure 31 shows the maximum individual AIS3+ probability for head injuries for each bus design at all impact speeds and positions for all VRU groups. The maxima for all groups are less for Px than for either B1 or B2. For the 50th percentile male cyclist and pedestrian, Px exhibits lower maxima than P0, although the maximum value for the 5th percentile female pedestrian is slightly higher.

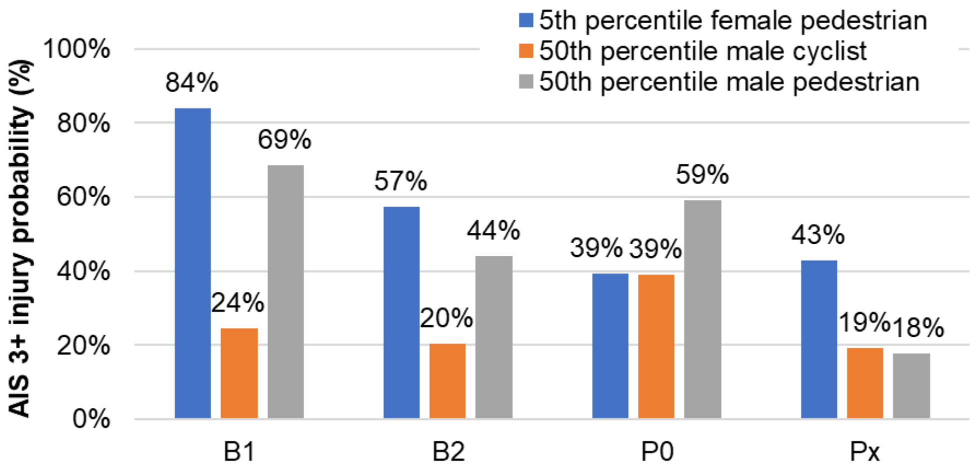



**Figure 31: Maximum individual head injury for each bus at all impact positions and speeds for each VRU group**

Table 38 shows the results of the run-over test for each bus design in the five impact positions at 10, 20 and 30mph. The table shows that B2 is predicted to run-over the VRU in four of the fifteen collision scenarios, while P0 is predicted to run-over them in only one scenario and Px is predicted to run over them in two scenarios. All three designs run-over the VRU when the impact occurs in position 3 (the centre of the bus) at 30mph. This collision configuration is the hardest to protect against run-overs since the VRU tends not to be thrown to the side, as occurs in collisions in the outer positions. In order to avoid being run-over the VRU must travel far enough that they come to rest beyond the point where the bus would be able to stop; in simulations in which the bus was travelling at 30mph that was assumed to be 25.69m. These binary results make no allowance for anything that might come into the VRU's path as they are being thrown clear of the bus. Clearly there is significant risk of injury from being thrown clear of the bus's path but striking some roadside feature or falling into the path of a vehicle in another lane.

**Table 38: Run-over results for each impact position, speed and bus design for the 50th percentile male pedestrian**

| | | Run-over or not | | |
|---|---|---|---|---|
| | | Bus Model | | |
| **Position** | **Speed** | **B2** | **P0** | **Px** |
| **1** | **10** | Pass | Pass | Pass |
| **2** | **10** | Pass | Pass | Pass |
| **3** | **10** | Pass | Pass | Pass |
| **4** | **10** | Pass | Pass | Pass |
| **5** | **10** | Pass | Pass | Pass |
| **1** | **20** | Pass | Pass | Run-over |
| **2** | **20** | Run-over | Pass | Pass |
| **3** | **20** | Pass | Pass | Pass |
| **4** | **20** | Pass | Pass | Pass |
| **5** | **20** | Pass | Pass | Pass |
| **1** | **30** | Run-over | Pass | Pass |
| **2** | **30** | Run-over | Pass | Pass |
| **3** | **30** | Run-over | Run-over | Run-over |
| **4** | **30** | Pass | Pass | Pass |
| **5** | **30** | Pass | Pass | Pass |

The reality of bus design is that a number of front-end geometries will likely give the desired effect of reduced injury. The random nature of collisions mean that an individual collision scenario may still be dangerous even when the bus design is on average safer. The key finding here is that P0 and Px are both improvements over B2, so represent an improved VRU frontal crashworthiness.

#### 6.2.3.7 Headform Impact Tests

Headform impacts were simulated for all four bus designs in all five impact positions. The headform was positioned 1598mm above the ground plane to match the approximate CoG height of the 50th percentile male head. Headform impacts were conducted at 10, 20 and 30mph to match the speeds used in the whole-body simulations. A further simulation was conducted at a velocity of 25mph (11.1m/s) to match the physical test requirement in the Bus Impact Test Standard.

Figure 32 shows the results of headform impact simulations at 10, 20 and 30mph in, all five impact positions, with B2, P0 and Px, correlated with equivalent data sets from simulations using a whole-body 50$^{th}$ percentile male EuroSID-2re pedestrian. The figure shows good correlations between equivalent data sets, with $R^2$ values above 0.73 for all buses. The figure also shows a significant positive offset in the headform data, indicating that a headform impact results in a $HIC_{15}$ value between 232 and 311 points higher than an equivalent impact with a whole-body dummy.

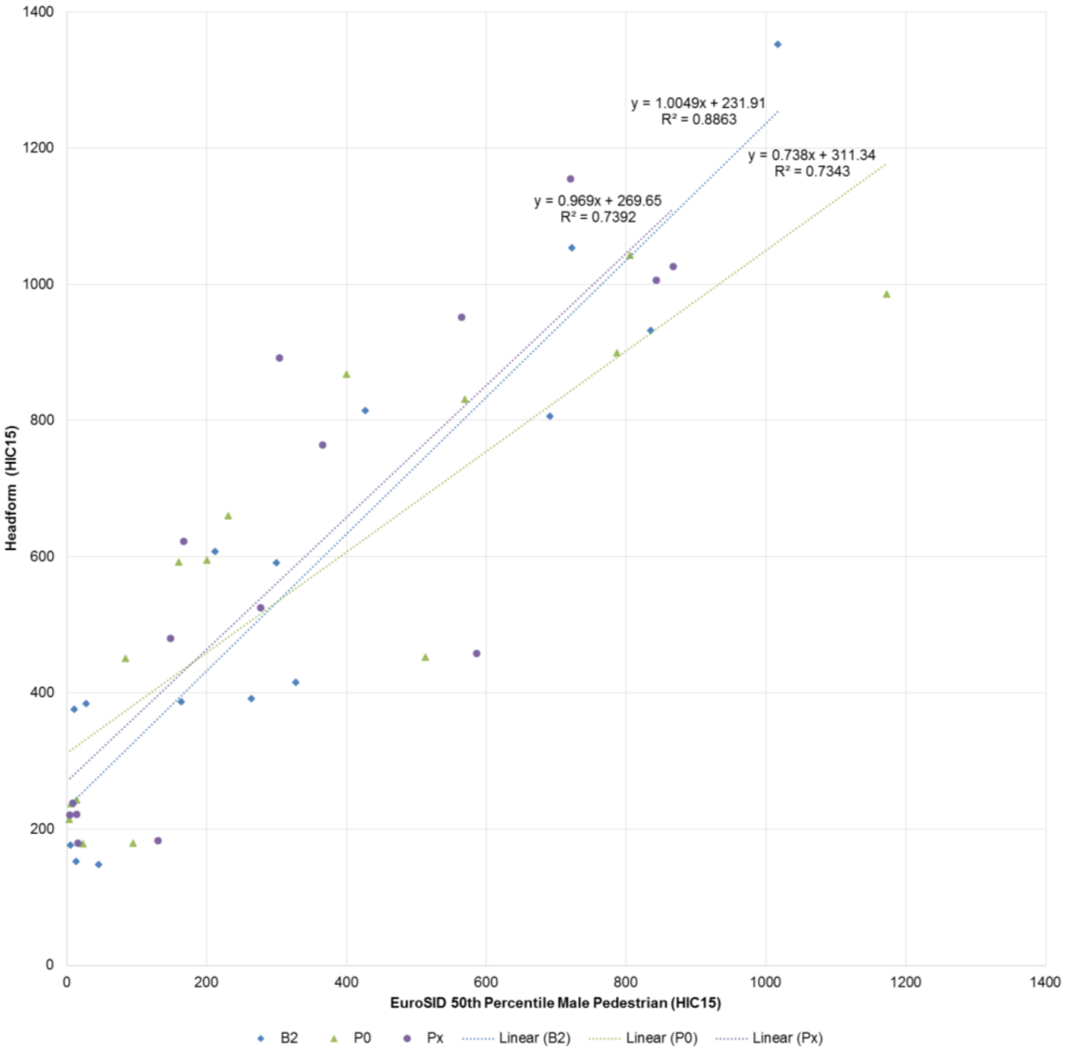



**Figure 32: Correlation between $HIC_{15}$ values from simulations using a headform (Y axis) and a 50$^{th}$ percentile male EuroSID-2re whole-body dummy**

#### *6.2.4 Conclusion and Recommendations*

Analyses of current bus front end designs and optimisation of design to reduce the injury risk to VRUs using simulation tools, helped to reach the following conclusions and recommendations

- Injury risk can be reduced by improved bus front-end design.
- Collisions between VRUs and buses are more likely to cause thoracic injuries with a severity of AIS3+ than head injuries.
- Current generation bus (B2) reduced the risk of AIS3+ head injury when compared to the previous generation bus (B1)
- The enhanced bus design (Px) on average reduces the probability of suffering an AIS3+ head injury (p = 6%) when compared to the current generation bus (B2) (p = 15%) for 50th percentile male pedestrians.
- Px on average reduces the probability of suffering an AIS3+ thoracic injury (p = 27%) when compared to B2 (p = 32%) for 50th percentile male pedestrians.
- Px on average reduce the probability of suffering an AIS3+ head injury for 5$^{th}$ percentile female pedestrians and 50$^{th}$ percentile male cyclists when compared to the current generation bus (B2).

#### *6.2.5 Limitations*

Currently no dummy is available that is capable of measuring thoracic injuries for female pedestrians. Given that thoracic injuries are more common in bus collisions than head injuries further work should be conducted to seek to address this data gap.

To date only the simulations using headforms have been validated against data derived from physical testing. Collecting a body of physical crash test data would permit the whole-body simulations to be validated and further refined.

### 6.3 VRU Front End Impact Testing

#### *6.3.1 Introduction*

Section 5.3.2 establishes that there is currently a paucity of a specific evidence base relating to establishing the effectiveness of impact energy absorbing structures at the bus front end. While a small number of case studies have been performed with computational models to show that impacts against a bus front end may have a lower risk of serious head injuries, there is no research investigating the real-world impact performance of bus front ends. As the majority of the energy absorption for VRU collisions is provided by the glazed areas of the bus front end, this is the critical area to investigate to understand real-world impact performance. Whilst the fracture mechanics of windscreens has been researched in depth, particularly for M1 passenger vehicles, there is currently no evidence base that evaluates the fracture mechanics of bus windscreens during impact loads. In particular, as the current generation of bus windscreens adopt a “wraparound” style, it is unknown how the radius of curvature of the windscreen affects outcomes.

The aim of this research is to therefore investigate the effect that the glazed areas of buses and their radius of curvature have on head injury risk by performing headform impact tests against the flat and wraparound areas of the windscreen glazing of a bus. Specifically, this research aims to compare the kinematics and injury risks associated with an impact at the front corners and centre of a wraparound bus windscreen. To achieve these aims an adult headform was impacted against the windscreen of a bus at two different impact locations to establish the differences in impact energy absorption between the locations. The following subsections therefore provide an overview of the methods employed by these headform impact tests and their outcomes.

### 6.3.2 Selection of Bus Front Ends

A single current generation bus front end test specimen with a wraparound windscreen was selected to test impacts against the flat and curved wraparound windscreen glazing sections. All key structural components and adhesives that were required to support the windscreen were specified, however, no bodywork was required (as there were no impacts against the bodywork and it did not provide any additional structural strength).

### 6.3.3 Headform

A spherical adult headform impactor conforming to UN Regulation 127 (Pedestrian Safety) and APROSYS HVAI test protocol requirements (see Section 7.3.2 and 7.3.3) was specified. A triaxial accelerometer was mounted within the recess of the headform at the centre of the sphere and filtered using a CFC 1000 filter, as defined in ISO 6487:2002.

### 6.3.4 Impact Points

Two impact points were selected based on a requirement to impact both a flat section and a wraparound section of the windscreen without the impact points being close enough on the single test specimen to result in interference between the first and second impacts. Using the zones defined by the APROSYS HVAI test protocol (see Section 7.3.3 & Figure 33 below), it was decided that the two impacts should be performed within zones A1A, to impact the wraparound section of the windscreen, and A6C, to impact a flatter part of the windscreen.


**Figure 33: Set up of APROSYS HVAI impact zones (left) and the wraparound windscreen impact test against the A1A impact position (right)**

The specific impact point in the A1A zone was 100 mm inwards and 125 mm upwards from the bottom right corner of the impact zone, whilst the impact point within the A6C zone was 125 mm inwards and 75 mm upwards from the bottom right corner of the impact zone.

### *6.3.5 Headform Impact Test Approach*

An impact rail gun was located perpendicular to the frontal plane of the bus at each impact point and used to accelerate the headform to an impact speed of 11.1 m/s (equivalent to a 25 mph/40 kph collision). The translational accelerations of the VRU head in the X/Y/Z axes were recorded during the primary impact, with the resultant head acceleration calculated from this data. Head injury criteria ($HIC_{15}$) values were then calculated for the primary impact during each test according to Equation 1 (see Section 0). Head injury risks were calculated from the recorded HIC values for the percentage risk of an AIS2+ head injury (equivalent to a serious head injury in STATS19). The probability of AIS2+ head injury (i.e. head injury risk) was then calculated according to the formula described in Equation 2. Results were compared to assess differences in headform kinematics and head injury risk between the two tests.

### *6.3.6 Evaluation of Results*

The resultant headform accelerations for each impact are shown below in Figure 34. Peak linear accelerations found to be greater for the wraparound section of the windscreen when compared to the flat section (364 *g* vs. 258 *g*). This was also reflected in the calculated $HIC_{15}$ values, where the wraparound windscreen section had a $HIC_{15}$ value of 1028 (49% AIS2+ head injury risk) and the flat section had a $HIC_{15}$ value of 774 (49% AIS2+ head injury risk). These results therefore show that head impacts against the wraparound section of a bus windscreen increase the risk of an AIS2+ head injury by around 36% when compared to the flatter sections of the windscreen.

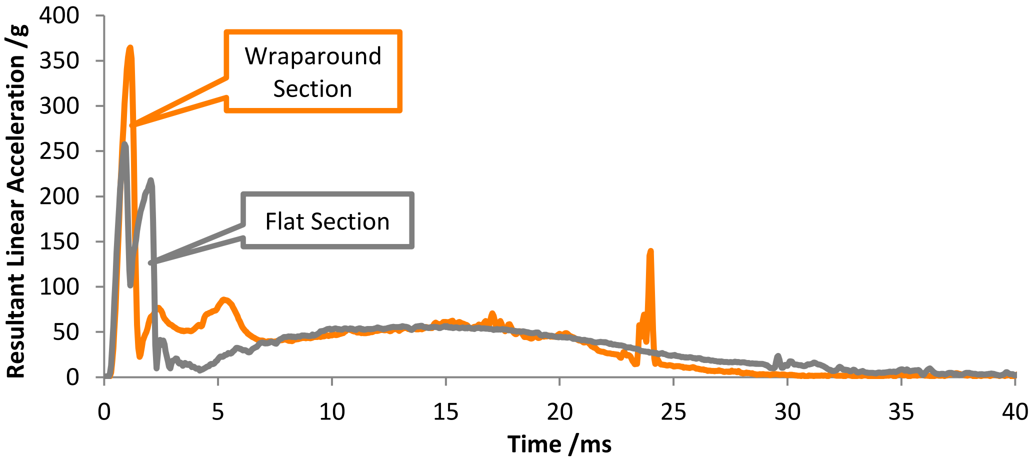



**Figure 34: Resultant linear accelerations for impacts against the wraparound (zone A1A) and flat (zone A6C) sections of the windscreen**

### 6.3.7 Conclusions

From these results in can be seen that the flatter section of the windscreen performs better than the curved wraparound section of the windscreen when considering the risks of AIS2+ head injuries. This is primarily due to the structural stiffness provided by the smaller radius of curvature adopted by the curved wraparound windscreen glazing when compared to the flatter section of the windscreen. It is therefore clear that larger radii of curvature should be recommended for the curved corners of the wraparound windscreens and encouraged for future enhanced bus front end geometries. These results also show that $HIC_{15}$ values as low as 775 during a 25 mph collision are achievable for current windscreen designs and so, with a future focus on safer glazing, further improvements in head impact safety may be possible. This could include setting ambitious targets for rewarding manufacturers that achieve $HIC_{15}$ values of less than 500 with their bus front end designs. This will require future innovations in the design and manufacture of bus windscreen glazing.

A number of key limitations exist for this research. Due to time and budget constraints, only two impacts against one windscreen test specimen were performed. Future research should consider more impacts across a wider range of impact points, impact speeds and bus front end models. In particular, the differences in performance between the A-pillar of a bus and the wraparound glazing of the bus should be determined to establish whether the use of a wraparound windscreen provides a benefit in comparison to a flat-fronted front end with A-pillars located at the front corners. Finally, the biofidelity of the spherical headform could be improved (perhaps using a Hybrid III headform instead). The purpose of this research was, however, to investigate the impact performance of a bus front end when adopting test and assessment procedures that could be used in the future. The use of the spherical headform specified by Regulation 127 was therefore seen as a reasonable limitation.

# 7 Existing Standards and Test Procedures

## 7.1 Introduction

The purpose of this section is to review the regulations, standards and protocols relevant to the VRU Frontal Crashworthiness (VCW) safety measure. This will be achieved by evaluating how each approach influences bus designs in the context of the Enhanced Front End Designs (FED), VRU Impact Protection (VIP), VRU Run-Over Protection (VRP) and Mirror Strike (MST) safety measures, whilst ensuring any unintended consequences for the driver, passengers and other road users are mitigated. Opportunities for implementation and potential issues raised in this review will then be used to inform future Bus Safety Standard (BSS) protocols.

The regulations, standards and protocols identified to be relevant to the FED, VIP, VRP and MST safety measures may be split up into four key sections, including:

Constraints on Vehicle Dimensions

- Weights and Dimensions Directives (96/53/EC, 2002/7/EC, 2015/719)
- EU Regulation 1230/2012 (Turning Circle)
- STRMTG Technical guide: Tramway front end design

VRU Impact Protection Requirements

- UN Regulation 43 (Safety Glazing)
- UN Regulation 127 (Pedestrian Safety)
- APROSYS Heavy Vehicle Aggressivity Index (HVAI)

VRU Run-Over Protection Requirements

- APROSYS Heavy Vehicle Aggressivity Index (HVAI)

Vehicle-to-Vehicle Crashworthiness

- UN Regulation 66 (Strength of Superstructures (Buses))
- UN Regulation 29 (Cab Strength)
- UN Regulation 93 (Front Underrun Protection Devices)

Each of the listed regulations, standards and protocols has been reviewed in the following sections. The testing and assessment protocols for each approach have been summarised, before critically appraising its relevance to the BSS and identifying any future developments.

## 7.2 Constraints on Vehicle Dimensions

### *7.2.1 Weights and dimensions directives*

Council Directive 96/53/EC set out maximum weights and dimensions for goods vehicles weighing more than 3.5 tonnes and passenger vehicles carrying more than nine persons ($M_2$ and $M_3$) (EC, 1996). Under this EC Directive, the maximum length for a rigid motor vehicle is 12 m (18 m for articulated buses), the maximum width is 2.55 m and maximum height is 4 m. The maximum weight for a two-axle rigid motor vehicle is 18 tonnes and 28 tonnes for a three-axle articulated bus.

In 2002, however, Directive 2002/7/EC amended Council Directive 96/53/EC by permitting longer buses (UNECE, 2002). The maximum permitted length of buses with two axles was raised from 12 m to 13.5 m and from 18 m to 18.75 m for articulated buses (i.e. the lengths of other motor vehicles remained the same). Other changes included permitting buses with more than two axles to reach 15 m in length and buses with trailers to reach 18.75 m.

In 2015, Directive (EU) 2015/719 amended Council Directive 96/53/EC to grant exemptions to the maximum permissible weight of a bus to account for the added weight of alternative fuel powertrains and the increasing average weight of passengers and their luggage (EU, 2015a). Under this Directive, buses with two axles are permitted to have an additional mass of 1.5 tonnes (19 tonnes), whilst articulated buses are permitted to have an additional mass of 1 tonne (29 tonnes).

It must be noted that, under certain conditions, Council Directive 96/53/EC permits member states to allow larger vehicle combinations in their own country than that required by the Weights and Dimensions Directives. In the EU, therefore, the maximum height for a bus is 4.00 m (EC, 1996), whilst in the UK the maximum height for a bus is 4.57 m (DVSA, 2013). No other differences between UK and EU requirements were observed.

### *7.2.2 Turning circle*

Regulation (EC) 1230/2012 sets out the maximum turning circle requirements for buses (EC, 2012a). A bus must be able to complete a 360° turn within the boundaries of two concentric circles (12.5 m outer radius and 5.3 m inner radius) without the outermost points of the bus extending beyond the boundaries of the outer/inner circle (EC, 2012a). A two axle rigid bus is therefore able to reach 13.5 m in length as the maximum swing out of the rear is 0.6 m.

Buses with more than two axles have a length limit of 15 m, but are often equipped with steered tag axles, whilst an articulated bus has a length limit of up to 18.75 m. The method of connection is comparable to a draw-bar HGV combination. The OECD found 18.75 m rigid draw-bar HGV combinations tend to have narrower swept paths than the 16.5 m articulated HGV length limit (whilst meeting the same turning requirements), as the prime mover and trailer unit wheel bases are shorter than the tractor semi-trailer combination (OCED, 2001).

Buses with curved profile front end designs may be able to further extend the length of the vehicle cab without conflicting with Regulation (EC) 1230/2012 requirements. Currently, $N_2$ and $N_3$ category vehicles are the only vehicles to receive cab length derogations that permit such an increase, however, any increase must demonstrate improved VRU safety, vehicle aerodynamics and HGV driver comfort (EU, 2015a). $N_2$ and $N_3$ vehicles have been shown to be able to extend the cab length by up to 850 mm without conflicting with Regulation (EC) 1230/2012 requirements (Knight, 2014). No such derogations exist for $M_2$ and $M_3$ vehicles.

### *7.2.3 Front end design of trams*

As discussed in Section 4.2.3, research in bus-to-VRU impacts, and run-over protection, is still in its early stages. Guidelines that underpin safer tram front end designs have, however, recently been developed by the STRMTG (2016). This design guide has been developed with the intention of improving the geometric design of the tram front end to reduce injury risks and to minimise the likelihood of a run-over event. This guide specifies that the front end of a tram must be designed to laterally deflect pedestrians during impacts.

To achieve this, the front end must have an angle of at least 15° in the horizontal plane (α) from a point 150 mm either side of the centreline of the tram and an angle of at least 30° from a point 300 mm inward from the edge of an impact surface, defined based on the edges of the main pillars at a height of 1.75 m. In addition to requirements for curvature in the horizontal plane, STRMTG also provide requirements for vertical raking (β) based on both the horizontal curvature of the front end design and which part of the tram is being assessed (i.e. windscreen (ws) or bumper (streamlining)). This is combined with a requirement for the outermost points of the front end to have the lowest Z (vertical) coordinates possible to ensure VRUs are hit below the knees (i.e. ≤ 350 mm). Finally, within the impact surface area, sharp edges and protruding components must have a minimum radius of 6 mm (10 mm recommended) or be covered (e.g. flood lights and wiper bosses).

### *7.2.4 Relevance to the Bus Safety Standard*

Council Directives 96/53/EC and 2002/7/EC, Directive (EU) 2015/719 and Regulation (EC) 1230/2012 define the fundamental design envelope for buses. Introducing curved profile bus front end designs will either improve the turning circle of a bus or could allow for an increase in vehicle length should additional frontal crashworthiness structures be permitted by future vehicle length derogations. Ultimately, these Directives and Regulations underpin the design envelope available for future improvements to the safety of the bus front end in terms of VRU frontal crashworthiness. STRMTG guidelines regarding tram front end designs, however, provide a precedent for defining minimum requirements for a geometric envelope that enhances the passive safety of bus front ends.

## 7.3 VRU Impact Protection Requirements

### *7.3.1 Windscreen safety*

UN Regulation 43 (Safety Glazing) specifies the mandatory requirements for the fitment of safety glazing materials as windscreens or other panes or partitioning on category L, M, N, O and T vehicles (UNECE, 2017). Regulation 43 prescribes a series of tests to assess the safety performance of the windscreen glazing across several key factors, including: fragmentation, mechanical strength (including ball and headform impact tests), environmental resistance, optical quality, glazing flexibility and resistance to chemicals and fire. Whilst all these tests are vital to ensure minimum safety requirements for VRUs that strike the glazed areas at the front end of the bus, it is clear, for the purposes of improving VRU safety through the Bus Safety Standard, that the most important test to review is the headform impact test.

The purpose of the headform test is to verify the compliance of glazing with requirements that limit injury in the event of impact of the head against the windscreen and other glazed areas of the vehicle. Regulation 43 requires headform impact tests to be performed for all windscreens, regardless of the material used, and for all rigid and flexible plastic materials used for the other glazed areas of motorised vehicles. Currently, headform impact tests may be conducted both with and without measuring the deceleration of the headform through two different testing and assessment protocols; with these protocols designated based on the type of safety glazing material to be installed.

The headform testing method described in paragraph 3.1 of Annex 3 (Test 3.1) defines the procedures performed for testing safety glazing without measuring headform decelerations. Headform impact tests may be performed on either a flat test piece or the internal face of a complete windscreen by dropping a laminated hardwood spherical/hemispherical headform, weighing 10 kg and covered with replaceable felt, from 1.5 m drop heights. The outcomes of such tests are considered satisfactory based on the condition of the glazing, in terms of the presence of circular cracks centred on the impact point and the absence of any large tears or separations between the glazing layers, after the impact.

The headform testing method described in paragraph 3.2 of Annex 3 (Test 3.2), however, defines the procedures performed when measuring the deceleration of the headform. Such tests are only performed against the internal face of the complete safety glazing structure by dropping a “phantom” headform (instrumented, constructed and calibrated as specified by the procedure), weighing 10 kg, from heights ranging between 1.5 m and 3 m. The outcomes of these tests are considered satisfactory if the test piece is not penetrated or broken into fully separated large pieces and if the Head Injury Criteria (HIC) values achieved during testing remain less than 1000.

### *7.3.2 Pedestrian safety*

Minimum pedestrian safety performance requirements for $M_1$ and $N_1$ category vehicles are specified by UN Regulation 127 (Pedestrian Safety) and UN Global Technical Regulation (GTR) No. 9 on Pedestrian Safety (UNECE, 2015b;UNECE, 2009). Both GTR No. 9 and Regulation 127 prescribe a series of tests to assess the safety performance of certain parts of the front end of the vehicle (bumper, bonnet, wings, scuttle, wiper spindles and lower windscreen frame) identified as causing injuries to pedestrians, as well as other VRUs, during collisions. The purpose of these regulations is to ensure a minimum level of protection is provided to VRUs during collisions involving the front end of a vehicle (UNECE, 2015b;UNECE, 2009).

Both regulations verify compliance of the vehicle with minimum requirements by specifying three impactor tests: a “legform to bumper” impact test, a “child headform” impact test and an “adult headform” impact test. Depending on the lower bumper height of the vehicle, the legform to bumper test impacts either a flexible lower legform (13.2 ± 0.4 kg) or rigid foam covered upper legform (9.5 ± 0.1 kg) impactor against the bumper test area of the vehicle at impact speeds of 11.1 ± 0.2 m/s. At least nine child headform impact tests are performed within a specified area by impacting the vehicle front end with an aluminium, child sized, spherical headform at an angle of 50 ± 2° and impact speed of 9.7 ± 0.2 m/s. Similarly, at least nine adult headform impact tests are also performed by impacting a specified area at the front end of the vehicle with an aluminium, adult sized, spherical headform at an angle of 65 ± 2° and impact speed of 9.7 ± 0.2 m/s.

Using specified instrumentation, each test measures the kinematic response of the impactor during impact before comparing these responses to a range of pass/fail criteria. The lower legform impactor in Regulation 127 measures knee ligament elongation and tibia bending moments to specify that the maximum elongation of the medial collateral, anterior cruciate and posterior cruciate ligaments shall not exceed 22 mm, 13 mm and 13 mm (respectively) and that the maximum tibia bending moment shall not exceed 340 Nm. The lower legform impactor in GTR No. 9, however, measures knee bending angles, knee shear displacements and upper tibia acceleration to specify maximum knee bending angles of 19°, knee shearing displacements of 6.0 mm and upper tibia accelerations of 170 *g*.

The upper legform impactor measures the instantaneous impact forces and femur bending moments, to specify that impact forces shall not exceed 7.5 kN and the femur bending moments shall not exceed 510 Nm. For both the child and adult headform impact tests, the impactors measure the tri-axial acceleration of the headform to specify that over two-thirds of the test area shall not have a Head Injury Criteria (HIC) value in excess of 1000, whilst the remaining test area shall not have a HIC value that exceeds 1700.

### 7.3.3 APROSYS Heavy Vehicle Aggressivity Index (HVAI)

The APROSYS Heavy Vehicle Aggressivity Index (HVAI) is a testing and assessment protocol that assesses three key aspects of passive safety in HGV design; the interaction of the VRU with the structures of a flat fronted vehicle during impacts (Structural Index), the influence of front end geometry on the likelihood of running the VRU over (Run-over Index) and the ability to provide the driver with a sufficient direct and indirect field of view (Active Index) (Smith, 2008). When considering the VRU Impact Protection safety measure reviewed in this section, it is clear the APROSYS HVAI Structural Index is most relevant to this safety measure.

The aim of Structural Index is to assess the structural behaviour of a flat fronted HGV during the primary impact with a VRU. It is comparable to UN Regulation 127 (Pedestrian Safety) in the case of $M_1$ and $N_1$ category vehicles (UNECE, 2015b). The protocol splits the front of the HGV into adult and child head height zones, with the upper boundary of these zones determined while the vehicle is at its minimum cab height and the lower boundary determined while the vehicle is at its maximum cab height (Smith, 2008).

The adult and child zones are divided in to six test zones, which are in turn sub-divided into quarters. One impact test point must be selected from each of the twelve test zones and is selected based on which is predicted to potentially cause the most severe injury to a VRU, with vehicle manufacturers able to request up to three further tests (one per test zone).

To test each selected test point, a headform is projected at a speed of 11.1 ± 0.2 m/s into the front end of the vehicle at an angle perpendicular to the surface where the test point is located. The 15 ms Head Injury Criteria ($HIC_{15}$) is used to determine safety performance. If the test point has a $HIC_{15}$ value of less than 1000 it will score two points (green), if the $HIC_{15}$ value is between 1000-1350 it will score one (yellow) and should the $HIC_{15}$ value be greater than 1350 it will score zero (red). Should extra test points be requested by the manufacturer, additional scores are given to the test zones.

### *7.3.4 Relevance to the Bus Safety Standard*

All three previously discussed testing and assessment protocols use a range of leg form and headform impactors to strike the frontal structures of the vehicle or test piece being tested. Despite this, none of the regulatory approaches specifically address the regulation of bus front end structures to improve VRU impact protection. Regulation 43 specifies impact tests and safety performance criteria for the internal aspects of bus windscreens and other safety glazing material, resulting in protection for internal occupants only. Regulation 127 specifies the pedestrian impact safety protection performance of $M_1$ and $N_1$ vehicles only, resulting in test and assessment procedures that would require significant revision to ensure relevance for flat-fronted buses.

While the HVAI Structural Index test and assessment protocol focuses on VRU impact safety performance for HGVs, the specified procedures may be directly applied to test and assess the VRU impact safety performance of flat-fronted $M_2$ and $M_3$ category vehicles. Although a number of test variables may have to change to ensure the protocols remain relevant to the collision mechanisms for VRU to bus impacts, the overall testing and assessment approach need not considerably change. When considering buses with curved front ends, however, it is clear that there will be several compatibility issues with the protocols developed the APROSYS project. As these protocols were proposed based on flat-fronted vehicle designs, these approaches will need to adapt to ensure that the VRU impact safety performances of curved front ends are appropriately assessed.

When considering the aspects of the HVAI testing and assessment protocols that will require an update, it is important to review each part of the protocol. Whilst the adult and child test zones and impact grid are highly relevant approaches, the upper and lower boundaries will need to be updated based upon the maximum and minimum ride heights of the current UK bus parc. For buses with curved front ends, however, the impact grid should be specified to wrap around the front end of the bus between the most forward points of the bus when at its maximum width and tests should still be performed at a normal angle to the structure.

The headforms used in the HVAI may be made more biofidelic in their response through the use of Hybrid III headforms rather than rigid metal headforms. As it has been recognised that rotational head accelerations are strongly linked to injury outcomes, the kinematics of the test headform should be measured across all six degrees of freedom (translational and rotational accelerations) and compared to state-of-the-art injury criteria. With the collision statistics showing that bus-to-VRU collisions may occur across a range of vehicle speeds, it is also important to specify minimum requirements for VRU impact performance during both medium (6.94 ± 0.2 m/s) and high (11.11 ± 0.2 m/s) speed manoeuvres. This will cover the range of bus speeds that occur in 50% of bus-to-VRU collisions associated with a VRU head injury and that do not involve a run-over event.

When considering the significant costs of physically performing these tests, it is important to provide an opportunity for manufacturers to reduce costs through the use of computational modelling. Both Regulation 29 (Section 7.5.1) and the HVAI allow vehicle certification through this route; however, there is a requirement for such computational models to be audited by notified bodies for quality assurance.

## 7.4 VRU Run-Over Protection Requirements

### *7.4.1 APROSYS Heavy Vehicle Aggressivity Index (HVAI)*

The APROSYS Heavy Vehicle Aggressivity Index (HVAI), as previously described, assesses the three key aspects of passive safety associated with HGV designs; the interaction of the VRU with the structures of a flat fronted vehicle during impacts (Structural Index), the influence of front end geometry on the likelihood of running the VRU over (Run-over Index) and the ability to provide the driver with a sufficient direct and indirect field of view (Active Index) (Smith, 2008). When considering the VRU Run-Over Protection safety measure reviewed in this section, it is clear that the HVAI Run-Over Index is most relevant to this safety measure.

The Run-Over Index assesses the effectiveness of the HGV design for preventing cyclists or pedestrians from being run-over during a collision by performing a total of 21 simulations of VRU-to-HGV collision scenarios. The simulation matrix was determined based upon collision data detailing the HGV impact location, the HGV and VRU manoeuvres and the VRU impact orientation (Table 39).

**Table 39: Run-over simulation matrix (Smith, 2008)**

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

To determine run-over risk, the VRU is classed as being run over if one of the body regions highlighted red comes in contact with one of the HGV wheels or if the centre of gravity of the head or hip falls within the defined critical area zone.

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

The run-over and secondary impact risk data are then weighted based on the incidence of run-over collisions associated with each HGV region to provide an overall run-over risk value for each HGV. Further information on the run-over index can be found in AP-SP21-0091.

### *7.4.2 Relevance to the Bus Safety Standard*

No existing regulatory approaches, for any vehicle category, attempt to address the issue of VRU run-over collisions through the improved regulation of vehicle designs.

This is despite run-overs forming a significant and critical aspect of the heavy vehicle collision landscape. The APROSYS HVAI does, however, provide a standardised protocol for testing the run-over safety performance of HGV designs via a simulation approach. This approach may therefore be utilised, with some future adaptions, for assessing the VRU run-over safety performance of future bus designs.

While the HVAI Run-Over Index test and assessment protocol focuses on the VRU run-over safety performance for HGVs, the specified procedures may also be directly applied to test and assess the VRU impact safety performance of flat-fronted $M_2$ and $M_3$ category vehicles. Although a number of test variables may have to change to ensure the protocols remain relevant to the collision mechanisms for VRU to bus impacts, the overall approach need not considerably change. As the run-over HVAI protocols were proposed to address the issue of HGVs with curved front end designs, these protocols would also be highly appropriate for certifying buses that adopt a curved front end design.

When considering the aspects of the HVAI Run-Over Index protocols that would require an update, it is important to review each part of the protocol. The weightings will clearly need to be updated to represent the incidence of VRU run-over collisions in Greater London that are associated with each bus region. With the collision statistics showing that bus-to-VRU collisions may occur across a range of speeds, it is also important to specify the minimum requirements for VRU run-over performance using the range of bus speeds and deceleration rates that are typical to bus-to-VRU collisions. It is also likely that the run-over regions used for the simulations would have to change due to the different axle configurations of buses when compared to HGVs.

Importantly, when considering the significant costs of physically performing these tests, it is important that the computational modelling approach is still adopted as this can be used to provide an opportunity for manufacturers to significantly reduce the costs of certification. Both Regulation 29 (see Section 7.5.1) and the HVAI allow vehicle certification through this route; however, there is a requirement for such computational models to be audited by the notified body for quality assurance purposes.

## 7.5 Vehicle-to-Vehicle Crashworthiness

### *7.5.1 Cab strength testing*

There are currently no mandatory crashworthiness performance requirements for frontal collisions involving $M_2$ and $M_3$ vehicles. UN Regulation 66 (Strength of Superstructures (Buses)) specifies mandatory structural and stability requirements for single deck rigid and articulated vehicles, designed to carry more than 16 passengers (including driver/crew), in the event of a roll-over incident (UNECE, 2005). UN Regulation 66 may, at the request of a manufacturer, be voluntarily applied to other $M_2$ or $M_3$ vehicles not within this scope. This Regulation ensures that the superstructure of the vehicle has sufficient strength to ensure that the residual space, comprising of the passenger, crew and driver compartments, during and after a rollover test on the complete vehicle remains preserved (UNECE, 2005).

UN Regulation 29 (Cabs of Commercial Vehicles) specifies the structural requirements for N category vehicles (UNECE, 2012b). Although Regulation 29 is not directly applicable to $M_2$ and $M_3$ category vehicles, Mercedes-Benz voluntarily tests the Citaro city bus against the Regulation 29 impact tests (Mercedes-Benz Bus UK, 2017). The purpose of Regulation 29 is to ensure that the survival space for the drivers of goods vehicle is maintained during a roll-over or head-on rear of trailer collision by impacting the vehicle cab with a combination of impactors representing these different collision scenarios. Manufacturers may use up to three cabs during the test process or, to reduce development costs, no physical tests need to be performed if the manufacturer provides evidence of structural integrity through either computer simulations or cab strength calculations.

The front impact test (Test A) is only conducted on cab-over-engine design goods vehicles (i.e. non-bonneted vehicles) and involves striking the front of the cab with a rectangular 1,500 kg steel impactor mounted to a pendulum. The test is set up to impact the foremost aspect of the vehicle with an impact energy of 55 kJ when in the vertical position (for $N_2$/$N_3$ category vehicles with a gross vehicle mass exceeding 7.5 tonnes). The front pillar impact test (Test B) is only conducted on $N_2$ and $N_3$ vehicles with a gross vehicle mass in excess of 7.5 tonnes and involves striking the windscreen and A-pillars with a rigid 1,000 kg cylindrical impactor mounted to a pendulum. The test impacts the foremost aspect of the vehicle at an impact energy of 29.4 kJ when the impactor is in the vertical position.

The roof strength test (Test C) is split into two tests; the dynamic pre-loading of the cab and the cab roof strength test. The dynamic pre-loading test is conducted on $N_3$ category vehicles and $N_2$ category vehicles with a gross vehicle mass in excess of 7.5 tonnes, whilst cab roof strength tests must be conducted for all N category vehicles. The dynamic pre-loading test strikes the cab with a flat rectangular rigid impactor, weighing no less than 1,500 kg, at an angle of 20° to the longitudinal plane of the cab and at an impact energy of no less than 17.6 kJ. The cab roof strength test applies a static load with a rectangular steel device positioned parallel to the X-Y plane of the chassis. The static load is applied along the vertical axis of the chassis, with the loading face of the device covering the whole area of the cab roof, to the maximum mass authorised for the front axle/s of the vehicle, but not exceeding 98 kN.

For all tests, the cab must provide adequate survival space to accommodate a manikin, as described in the regulation (a 50th percentile Hybrid II or III male dummy, with or without measuring instrumentation may be used), when it is seated in the median seat position. No contact should be made between the manikin and non-resilient parts with a Shore-Hardness of 50 or more or parts which may be moved away from the manikin by using a force of less than 100 N.

### *7.5.2 Front underrun protection*

There are also no mandatory requirements for front underrun protection (FUP) devices for collisions involving $M_2$ and $M_3$ vehicles. UN Regulation 93 (Front Underrun Protection Devices) specifies the design and installation of front underrun protection devices intended to be fitted to $N_2$ and $N_3$ category vehicles (excluding $N_2$G and $N_3$G variants) (UNECE, 1994). The purpose of the Regulation is to ensure compatibility of the HGV front ends with both passenger cars ($M_1$) and light vans ($N_1$) during head-on collisions through absorbing greater impact energies and preventing the underrun of the car during impact (UNECE, 1994).

FUPDs must have a minimum height of 100 mm for $N_2$ and 120 mm for $N_3$ category vehicles and a ground clearance of no greater than 400 mm. FUPDs must cover the full width of the vehicle, to within 100 mm of the outer edges of the tyres. Static test loads equal to 50% the maximum vehicle weight (but not exceeding 80 kN) and 100% the maximum vehicle weight (but not exceeding 160 kN) are applied successively to the FUPD at the $P_1$ and $P_2$ test points, respectively, for at least 0.2 seconds. During testing, the rearwards deformation (measured from the foremost part of the vehicle to the front of the FUPD) of the test point cannot exceed 400 mm, whilst the maximum ground clearance (measured to the underside of the FUPD between the two $P_1$ points) cannot exceed 450 mm.

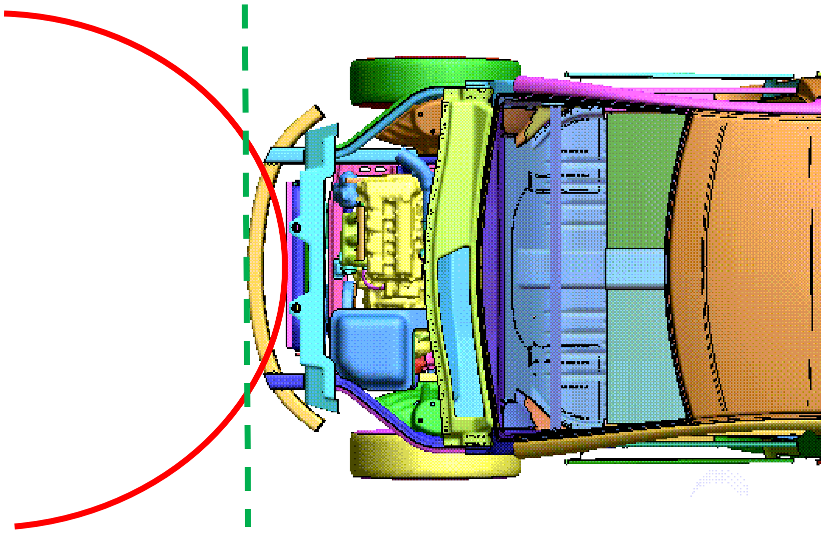


**Figure 35: Schematic illustrating possible interaction of curved FUP (red) with car structure at moment contact is made with car longitudinals (Knight, 2016)**

Buses with curved front end profiles provide an option to increase the deformation length available for FUP devices (Knight, 2016). This would increase the energy absorbing capacity of the bus in a collision, thus reducing the proportion of the total collision energy absorbed by a car, the energies transferred to the occupant and the intrusion into the passenger cell. Good structural interaction between vehicles is, however, a pre-requisite of good energy absorption. To ensure the potential energy absorption benefits of curved FUP devices are realised, it will be necessary to develop and implement requirements that ensure good structural interaction between buses and passenger cars. This is because, depending on the impact configuration, curved bus front ends could penetrate further into the car to interact adversely with the engine block (Figure 35) or introduce non-axial loading (Figure 36).

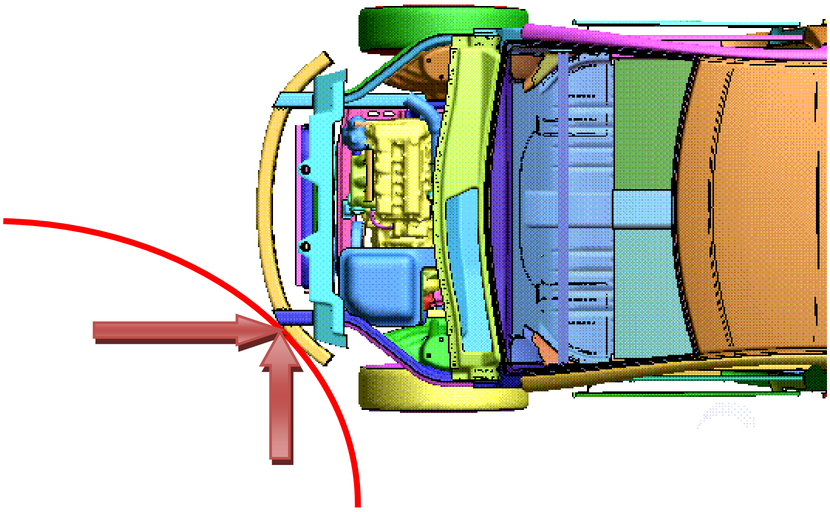


**Figure 36: Schematic illustrating potential deflection effect caused by the non-axial loading of the car by a curved FUP in an offset collision (Knight, 2016)**

### *7.5.3 Relevance to the Bus Safety Standard*

There are currently no mandatory frontal vehicle crashworthiness requirements for $M_2$ and $M_3$ category vehicles. This is important to recognise within this particular safety measure as, should improvements in VRU safety be achieved via improving the frontal crashworthiness of buses, this should not be at the expense of the safety of other road users, bus occupants or bus drivers. It is therefore important to ensure current safety levels for other road users and bus occupants be at least maintained, if not improved, by the Bus Safety Standard.

Bus front end structures that are developed to better protect VRUs are unlikely to include energy absorbing structures, or adopt front end profiles, that are of benefit during collisions with other vehicles. In the worst case scenario, these VRU frontal crashworthiness solutions may prove detrimental to the outcomes from bus collisions with other vehicles. Absorbent front end structures, which aim to reduce the impact energies experienced by VRUs, may result in greater levels of intrusion into the bus. Curved front end profiles, however, which are designed to deflect VRUs away from the bus wheels, may result in a greater penetration into the car before engaging crashworthiness structures and the introduction of non-axial loads to the crashworthiness structures, causing the transfer of greater impact energies to the occupants of the passenger car.

As frontal crashworthiness Regulations currently exist for N category vehicles (Regulations 29 and 93), several opportunities exist to adapt the testing and assessment approaches to ensure relevant protocols are developed for $M_2$ and $M_3$ category vehicles. The feasibility of adopting these Regulations has already been explored, in some part, with Mercedes-Benz Buses voluntarily putting Citaro city buses through Regulation 29 front impact tests (Test A). With the collision statistics showing a significant proportion of collisions between buses and both passenger cars and HGVs (Section 3.3), it is therefore clear that minimum performance requirements for the frontal vehicle crashworthiness of a bus may be important to ensuring there are no unintentional consequences for other road users as a result of introducing the Bus Safety Standard.

# 8 Cost-Benefit Analysis

## 8.1 Target population

The annual target population in 2018 estimated for all outcome severities (fatal, serious and slight casualties) relevant to the vulnerable road user (VRU) frontal crashworthiness (VCW) safety measure are presented in Table 40 below. Target populations were calculated for VRUs only (pedestrians, cyclists and PTWs), as this is the target population primarily affected by improvements in the frontal crashworthiness performance of buses. The selection of the appropriate target populations was performed to include the average annual number of casualties involved in bus collisions in London, where the VRU struck the area at the front end of the bus most relevant to the particular safety measure solution and was either run-over or thrown by the bus (see Section 1 for further information on the target population calculations for each safety measure solution).

Data was abstracted from the UK STATS19 road safety database and compared to run-over and front end impact location information from Edwards *et al*. (2018) and bus mirror strike data from the IRIS database. Target populations for the minimum and enhanced geometric requirements were split into two categories based on the key intervention phases that this safety measure affects. The enhanced geometric requirements, along with both the energy absorbing structures and deployable run-over guard safety measures, focus on VRU impacts across the entire length of the bus front end, whilst the minimum geometric requirements focuses on VRU impacts against the most lateral 0.5 m sections of the bus front end. One-third of VRU fatalities that impacted the bus front end were observed to be run-over by the bus, therefore all fatal and serious injury target populations associated with bus front end impacts were modified accordingly. VRU mirror strike target populations were abstracted from the IRIS database. Mirror strikes against roadside objects (e.g. trees, street furniture, etc.), relevant to the Class II mirror replacement and energy absorbing mirrors solutions, were designated as minor damage-only collisions.

**Table 40: Estimated average annual target population in 2018 for the VRU frontal crashworthiness [VCW] safety measure solutions**

| Safety Measure Solution | Casualty Type | Outcome Severity | | | |
|---|---|---|---|---|---|
| | | Fatal Casualties | Serious Casualties | Slight Casualties | Minor Damage |
| **Minimum Geometric Requirements (Primary Impact)** | Pedestrians | 1.1 | 7.3 | 34.8 | - |
| | Cyclists | 0.1 | 0.6 | 6.5 | - |
| | PTWs | 0 | 0.4 | 3.1 | - |
| | Damage-Only | - | - | - | - |
| | **Totals** | **1.2** | **8.4** | **44.4** | **-** |
| **Minimum Geometric Requirements (Run-Over)** | Pedestrians | 0.6 | 3.7 | 0 | - |
| | Cyclists | 0 | 0.3 | 0 | - |
| | PTWs | 0 | 0.2 | 0 | - |
| | Damage-Only | - | - | - | - |
| | **Totals** | **0.6** | **4.2** | **0** | **-** |

| Safety Measure Solution | Casualty Type | Outcome Severity | | | |
|---|---|---|---|---|---|
| | | Fatal Casualties | Serious Casualties | Slight Casualties | Minor Damage |
| **Enhanced Geometric Requirements (Primary Impact)** | Pedestrians | 4.6 | 30.5 | 144.9 | - |
| | Cyclists | 0.3 | 2.6 | 27.0 | - |
| | PTWs | 0.1 | 1.7 | 13.1 | - |
| | Damage-Only | - | - | - | - |
| | **Totals** | **5.1** | **34.9** | **185.0** | **-** |
| **Enhanced Geometric Requirements (Run-Over)** | Pedestrians | 2.3 | 15.3 | 0 | - |
| | Cyclists | 0.2 | 1.3 | 0 | - |
| | PTWs | 0.1 | 0.9 | 0 | - |
| | Damage-Only | - | - | - | - |
| | **Totals** | **2.5** | **17.4** | **0** | **-** |
| **Repositioning of Windscreen Wipers** | Pedestrians | 0.6 | 4.1 | 13.0 | - |
| | Cyclists | 0.1 | 0.4 | 2.4 | - |
| | PTWs | 0 | 0.2 | 1.2 | - |
| | Damage-Only | - | - | - | - |
| | **Totals** | **0.7** | **4.7** | **16.7** | **-** |
| **Energy Absorbing Structures** | Pedestrians | 4.6 | 30.5 | 144.9 | - |
| | Cyclists | 0.3 | 2.6 | 27.0 | - |
| | PTWs | 0.1 | 1.7 | 13.1 | - |
| | Damage-Only | - | - | - | - |
| | **Totals** | **5.1** | **34.9** | **185.0** | **-** |
| **Deployable Run-Over Guards** | Pedestrians | 2.3 | 15.3 | 0 | - |
| | Cyclists | 0.2 | 1.3 | 0 | - |
| | PTWs | 0.1 | 0.9 | 0 | - |
| | Damage-Only | - | - | - | - |
| | **Totals** | **2.5** | **17.4** | **0** | **-** |
| **Class II Mirror CMS Replacement** | Pedestrians | 0 | 8.0 | 5.0 | - |
| | Cyclists | 0 | 0 | 0 | - |
| | PTWs | 0 | 0 | 0 | - |
| | Damage-Only | - | - | - | 3,350 |
| | **Totals** | **0** | **8.0** | **5.0** | **3,350** |
| **Energy Absorbing Mirrors** | Pedestrians | 0 | 8.0 | 5.0 | - |
| | Cyclists | 0 | 0 | 0 | - |
| | PTWs | 0 | 0 | 0 | - |
| | Damage-Only | - | - | - | 3,350 |
| | **Totals** | **0** | **8.0** | **5.0** | **3,350** |

## 8.2 Estimates of effectiveness

The overall effectiveness values estimated for all outcome severities relevant to the VRU frontal crashworthiness safety measure (fatal, serious and slight casualties) are presented in Table **41** 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 5 and Section 6, the following paragraphs summarise the approaches adopted for calculating overall effectiveness values for each safety measure solution.

Overall effectiveness values for the geometric performance requirements were determined for each of the two key intervention phases. These were based on the London bus specific simulation work performed in Section 6, where the head injury and run-over risk safety performance of previous generation flat-fronted bus designs were compared to the risks associated with compliant bus front end designs. The reduction in head injury risks were calculated by assuming the mitigation of injuries to a less severe injury level, with the levels determined based on assuming that ~75% of mitigated injuries would be reduced to the level directly below the current injury severity level, whilst the remaining ~25% of mitigated injuries would be mitigated to two levels below the current injury severity level (including to the casualties prevented level). Run over risks were mitigated to the level below the current injury severity level only. Furthermore, due to the uncertainty surrounding these simulated values, a range of ±5% (or ±10% when mitigated to the below level only) was applied to the overall effectiveness values. For the minimum geometric requirements, it was found that any VRU impacts against the lateral aspects of the bus front end would result in an overall 60% reduction in AIS2+ head injury risk, whilst there was no expected reduction in the run-over risks. For the enhanced geometric requirements, it was found that any VRU impacts against the bus front end would result in an overall 74% reduction in AIS2+ head injury risk, whilst run-over risks would reduce by 56%.

When considering the energy absorbing structures safety measure solution, the results from the headform impact tests performed in Section 6 were used, alongside the future proposed VRU impact test requirements, to evaluate the relative reduction in head injury risk. Head injury risk reductions were calculated by assuming the mitigation of injuries to a less severe injury level. These levels were determined based on assuming ~75% of mitigated injuries would be reduced to the level directly below the current injury severity level, whilst the remaining ~25% of injuries would be mitigated to two levels below the current severity level (including to the casualties prevented level). Again, due to the uncertainty surrounding the simulated values, a range of ±5% (or ±10% when mitigated to the below level) was applied to the overall effectiveness values. For the impact test requirements, it was found that any VRU impacts against the bus front end would result in a 45% reduction in AIS2+ injury risk.

For the repositioning of the windscreen wipers safety measure, the removal of this specific risk was assumed to have a 90-100% likelihood of reducing the injury risks of a collision with the front end of the bus, where a windscreen wiper boss would have been impacted, by one injury severity level. This was because, although the VRU would now no longer impact the rigid windscreen wiper boss, the front end of the bus would still impact the VRU causing a less severe injury. A similar approach was also adopted for the deployable run-over guard, with the assumption that a run-over guard would prevent 90-100% of run-over events from occurring. To be run-over by a bus, however, the VRU would have to have been impacted by the bus in the first place, meaning that the injury risks of a collision with the bus front end, where a run-over event would have occurred, are only reduced by one injury severity level.

**Table 41: Estimated overall effectiveness ranges for incidents prevented for the VRU frontal crashworthiness [VCW] safety measure solutions**

| Safety Measure Solution | Casualty Type | Incidents Prevented | | | | Incidents Mitigated | | |
|---|---|---|---|---|---|---|---|---|
| | | Fatal Casualties | Serious Casualties | Slight Casualties | Minor Damage | Fatal to Serious | Fatal to Slight | Serious to Slight |
| Minimum Geometric Requirements (Primary Impact) | Pedestrians | 0% | 10-20% | 50-70% | - | 40-50% | 10-20% | 40-50% |
| | Cyclists | 0% | 10-20% | 50-70% | - | 40-50% | 10-20% | 40-50% |
| | PTWs | 0% | 10-20% | 50-70% | - | 40-50% | 10-20% | 40-50% |
| | Damage-Only | - | - | - | - | - | - | - |
| Minimum Geometric Requirements (Run-Over) | Pedestrians | 0% | 0% | 0% | - | 0% | 0% | 0% |
| | Cyclists | 0% | 0% | 0% | - | 0% | 0% | 0% |
| | PTWs | 0% | 0% | 0% | - | 0% | 0% | 0% |
| | Damage-Only | - | - | - | - | - | - | - |
| Enhanced Geometric Requirements (Primary Impact) | Pedestrians | 0% | 15-25% | 65-85% | - | 50-60% | 15-25% | 50-60% |
| | Cyclists | 0% | 15-25% | 65-85% | - | 50-60% | 15-25% | 50-60% |
| | PTWs | 0% | 15-25% | 65-85% | - | 50-60% | 15-25% | 50-60% |
| | Damage-Only | - | - | - | - | - | - | - |
| Enhanced Geometric Requirements (Run-Over) | Pedestrians | 0% | 0% | 0% | - | 46-66% | 0% | 46-66% |
| | Cyclists | 0% | 0% | 0% | - | 46-66% | 0% | 46-66% |
| | PTWs | 0% | 0% | 0% | - | 46-66% | 0% | 46-66% |
| | Damage-Only | - | - | - | - | - | - | - |
| Repositioning of Windscreen Wipers | Pedestrians | 0% | 0% | 90-100% | - | 90-100% | 0% | 90-100% |
| | Cyclists | 0% | 0% | 90-100% | - | 90-100% | 0% | 90-100% |
| | PTWs | 0% | 0% | 90-100% | - | 90-100% | 0% | 90-100% |
| | Damage-Only | - | - | - | - | - | - | - |
| Energy Absorbing Structures | Pedestrians | 0% | 10-20% | 35-55% | - | 25-35% | 10-20% | 25-35% |
| | Cyclists | 0% | 10-20% | 35-55% | - | 25-35% | 10-20% | 25-35% |
| | PTWs | 0% | 10-20% | 35-55% | - | 25-35% | 10-20% | 25-35% |
| | Damage-Only | - | - | - | - | - | - | - |
| Deployable Run-Over Guards | Pedestrians | 0% | 0% | 0% | - | 90-100% | 0% | 90-100% |
| | Cyclists | 0% | 0% | 0% | - | 90-100% | 0% | 90-100% |
| | PTWs | 0% | 0% | 0% | - | 90-100% | 0% | 90-100% |
| | Damage-Only | - | - | - | - | - | - | - |
| Class II Mirror CMS Replacement | Pedestrians | 90-100% | 90-100% | 90-100% | - | 0% | 0% | 0% |
| | Cyclists | 90-100% | 90-100% | 90-100% | - | 0% | 0% | 0% |
| | PTWs | 90-100% | 90-100% | 90-100% | - | 0% | 0% | 0% |
| | Damage-Only | - | - | - | 90-100% | - | - | - |
| Energy Absorbing Mirrors | Pedestrians | 0% | 10-20% | 35-55% | - | 25-35% | 10-20% | 25-35% |
| | Cyclists | 0% | 10-20% | 35-55% | - | 25-35% | 10-20% | 25-35% |
| | PTWs | 0% | 10-20% | 35-55% | - | 25-35% | 10-20% | 25-35% |
| | Damage-Only | - | - | - | 0% | - | - | - |

The risks of a mirror strike occurring are reduced by 90-100% through the replacement of Class II mirrors with a Class II CMS. Due to the flexibilities in camera placement, Class II CMS can raise the height of the camera from the ground and reduce the camera profile (relative to a Class II mirror), to reduce the risks of mirror strikes occurring to close to zero. Energy absorbing mirrors were presumed to mitigate the risks of a serious head injury to a similar extent as the energy absorbing structures safety measure solution, whilst it was assumed that there was no change in risk for damage-only mirror strikes. It should be noted that this was, however, an optimistic estimate of effectiveness, as this assumed the worst case performance.

## 8.3 Fleet fitment and implementation timescales

Timescales were determined for retrofit and new-build VRU frontal crashworthiness safety measure solutions to develop fleet fitment and policy implementation roadmaps for each solution (Table 42). 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 estimates for current levels of fleet fitment and expected years to full fleet fitment after implementation for each solution. Please see the stakeholder consultation report for further information on stakeholder feedback on fleet fitment and policy implementation timescales.

**Table 42: 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 Geometric Requirements** | 2019 | 2021 | 60% | N/A | 5 |
| **Enhanced Geometric Requirements** | 2022 | 2024 | 0% | N/A | 12 |
| **Repositioning of Windscreen Wipers** | 2019 | 2021 | 70% | N/A | 4 |
| **Energy Absorbing Structures** | 2021 | 2024 | 0% | N/A | 12 |
| **Deployable Run-Over Guards** | 2023 | 2024 | 0% | N/A | 12 |
| **Class II Mirror CMS Replacement** | 2020 | 2021 | 0% | 3 | 12 |
| **Energy Absorbing Mirrors** | 2019 | 2019 | 5% | 2 | 12 |

## 8.4 Casualty benefits

Table **43** 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 VRU frontal crashworthiness safety measure solutions. Outcomes are then monetised to estimate the total value of these casualty reductions to society.

**Table 43: Estimated total change in number and total value (NPV) of casualties over the 2019-2031 analysis period for the new-build VRU frontal crashworthiness [VCW] safety measure solutions (casualty increases are shown in (parentheses))**

| Safety Measure Solution | Casualty Type | Number of Incidents (n) | | | | Total Value (NPV) of Incidents (£M) |
|---|---|---|---|---|---|---|
| | | Fatal Casualties | Serious Casualties | Slight Casualties | Minor Damage | |
| **Minimum Geometric Requirements** | Pedestrians | 2.26-3.17 | 13.2-18.7 | 58.8-83.8 | - | 7.83-11.04 |
| | Cyclists | 0.22-0.31 | 1.5-2.2 | 16.2-22.9 | - | 0.97-1.37 |
| | PTWs | 0.06-0.09 | 0.7-1.1 | 5.4-7.6 | - | 0.35-0.50 |
| | Damage-Only | - | - | - | - | - |
| | **Totals** | **2.54-3.56** | **15.5-22.0** | **80.4-114.3** | **-** | **9.16-12.92** |
| **Enhanced Geometric Requirements** | Pedestrians | 15.2-20.4 | 88.6-119.6 | 268.2-352.6 | - | 50.41-67.66 |
| | Cyclists | 1.54-2.07 | 10.8-14.5 | 82.1-107.6 | - | 6.34-8.48 |
| | PTWs | 0.41-0.55 | 5.0-6.7 | 25.1-33.0 | - | 2.17-2.90 |
| | Damage-Only | - | - | - | - | - |
| | **Totals** | **17.2-23.1** | **104.3-140.8** | **375.4-493.2** | **-** | **58.92-79.04** |
| **Repositioning of Windscreen Wipers** | Pedestrians | 1.83-2.04 | 10.3-11.5 | 26.3-29.2 | - | 5.93-6.59 |
| | Cyclists | 0.18-0.19 | 1.2-1.3 | 8.1-9.0 | - | 0.70-0.77 |
| | PTWs | 0.05-0.06 | 0.6-0.7 | 2.6-2.9 | - | 0.26-0.29 |
| | Damage-Only | - | - | - | - | - |
| | **Totals** | **2.06-2.29** | **12.1-13.5** | **37.0-41.1** | **-** | **6.89-7.65** |
| **Energy Absorbing Structures** | Pedestrians | 6.80-10.68 | 40.3-64.1 | 179.9-287.4 | - | 23.61-37.35 |
| | Cyclists | 0.68-1.07 | 4.8-7.7 | 51.3-81.2 | - | 3.06-4.84 |
| | PTWs | 0.18-0.29 | 2.2-3.5 | 16.2-25.7 | - | 1.05-1.66 |
| | Damage-Only | - | - | - | - | - |
| | **Totals** | **7.66-12.04** | **47.3-75.3** | **247.4-394.3** | **-** | **27.72-43.85** |
| **Deployable Run-Over Guards** | Pedestrians | 6.94-7.71 | 39.1-43.5 | (51.2)-(46.1) | - | 20.02-22.25 |
| | Cyclists | 0.71-0.79 | 4.8-5.3 | (6.1)-(5.5) | - | 2.19-2.44 |
| | PTWs | 0.19-0.21 | 2.2-2.5 | (2.7)-(2.4) | - | 0.76-0.84 |
| | Damage-Only | - | - | - | - | - |
| | **Totals** | **7.83-8.70** | **46.2-51.3** | **(60.0)-(54.0)** | **-** | **22.98-25.53** |
| **Class II Mirror CMS Replacement** | Pedestrians | 0 | 42.9-47.7 | 26.8-29.8 | - | 9.28-10.31 |
| | Cyclists | 0 | 0 | 0 | - | 0 |
| | PTWs | 0 | 0 | 0 | - | 0 |
| | Damage-Only | - | - | - | 17881-19868 | 17.83-19.81 |
| | **Totals** | **0** | **42.9-47.7** | **26.8-29.8** | **17881-19868** | **27.11-30.12** |
| **Energy Absorbing Mirrors** | Pedestrians | 0 | 19.4-30.5 | (1.7)-(0.3) | - | 3.98-6.30 |
| | Cyclists | 0 | 0 | 0 | - | 0 |
| | PTWs | 0 | 0 | 0 | - | 0 |
| | Damage-Only | - | - | - | 0 | - |
| | **Totals** | **0** | **19.4-30.5** | **(1.7)-(0.3)** | **0** | **3.98-6.30** |

Table 44 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 VRU frontal crashworthiness safety measure solutions. Outcomes are then monetised to estimate the total value of these casualty reductions to society. It should be noted, from Table 42, that it was only possible to retrofit the Class II Mirror CMS Replacement and Energy Absorbing Mirrors safety measure solutions.

**Table 44: Estimated total change in number and total value (NPV) of casualties over the 2019-2031 analysis period for the retrofit VRU frontal crashworthiness [VCW] safety measure solutions (casualty increases are shown in (parentheses))**

| Safety Measure Solution | Casualty Type | Number of Incidents (n) | | | | Total Value (NPV) of Incidents (£M) |
|---|---|---|---|---|---|---|
| | | Fatal Casualties | Serious Casualties | Slight Casualties | Minor Damage | |
| **Class II Mirror CMS Replacement** | Pedestrians | 0 | 76.7-85.2 | 47.9-53.3 | - | 16.64-18.49 |
| | Cyclists | 0 | 0 | 0 | - | 0 |
| | PTWs | 0 | 0 | 0 | - | 0 |
| | Damage-Only | - | - | - | 31985-35539 | 32.00-35-55 |
| | **Totals** | **0** | **76.7-85.2** | **47.9-53.3** | **31985-35539** | **48.64-54.04** |
| **Energy Absorbing Mirrors** | Pedestrians | 0 | 33.6-52.7 | (3.0)-(0.6) | - | 6.92-10.94 |
| | Cyclists | 0 | 0 | 0 | - | 0 |
| | PTWs | 0 | 0 | 0 | - | 0 |
| | Damage-Only | - | - | - | 0 | - |
| | **Totals** | **0** | **33.6-52.7** | **(3.0)-(0.6)** | **-** | **6.92-10.94** |

## 8.5 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 on-going 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 associated stakeholder consultation report, the following paragraphs summarise the cost values utilised by this project for each safety measure solution and key cost category.

In order to estimate the expected changes in technology development, manufacturing and certification costs for each safety measure solution, initial baseline cost data was gathered through the stakeholder consultation process. This provided bus industry agreed ranges for estimated changes in both retrofit and new-build technology costs for each safety measure solution. This included costs changes relating to extra tooling and certification requirements for new-build buses, which were estimated by the bus industry for the costs associated with the minimum geometric requirements, the energy absorbing structures and the enhanced geometric requirements. Costs relating to new components were also included, with the costs associated with deployable run-over guards for new-build buses and energy absorbing mirrors and Class II CMS systems for retrofit systems and new-build buses. The repositioning of windscreen wipers during the design of new-build buses was assumed to be cost neutral. This was then 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 (see Table 45 and Table 46).

**Table 45: Estimated changes in costs per bus (NPV) and total fleet costs (NPV) over the 12-year analysis period (2019-2031) for the new-build VRU frontal crashworthiness [VCW] safety measure solutions (cost reductions are shown in (parentheses))**

| Safety Measure Solution | Cost Description | Cost (NPV) per bus (£) | Total Cost (NPV) (£M) |
|---|---|---|---|
| **Minimum Geometric Requirements** | Change in Technology Costs | 43-86 | 0.46-0.92 |
| | Change in Implementation Costs | 0 | 0 |
| | Change in Operational Costs | 0 | 0 |
| | Change in Insurance Claims Costs | (146)-(83) | (1.56)-0.89 |
| | **Totals** | **(103)-3** | **(1.10)-0.03** |
| **Enhanced Geometric Requirements** | Change in Technology Costs | 465-931 | 3.35-6.70 |
| | Change in Implementation Costs | 0 | 0 |
| | Change in Operational Costs | 0 | 0 |
| | Change in Insurance Claims Costs | (787)-(477) | (5.67)-(3.43) |
| | **Totals** | **(322)-454** | **(2.31)-3.27** |
| **Repositioning of Windscreen Wipers** | Change in Technology Costs | 0 | 0 |
| | Change in Implementation Costs | 0 | 0 |
| | Change in Operational Costs | 0 | 0 |
| | Change in Insurance Claims Costs | (77)-(57) | (0.82)-(0.61) |
| | **Totals** | **(77)-(57)** | **(0.82)-(0.61)** |
| **Energy Absorbing Structures** | Change in Technology Costs | 373-559 | 2.83-4.25 |
| | Change in Implementation Costs | 0 | 0 |
| | Change in Operational Costs | 0 | 0 |
| | Change in Insurance Claims Costs | (508)-(256) | (3.86)-(1.94) |
| | **Totals** | **(135)-303** | **(1.03)-2.31** |
| **Deployable Run-Over Guards** | Change in Technology Costs | 465-930 | 3.16-6.32 |
| | Change in Implementation Costs | 0 | 0 |
| | Change in Operational Costs | 221-618 | 1.50-4.20 |
| | Change in Insurance Claims Costs | (126)-(100) | (0.86)-(0.68) |
| | **Totals** | **560-1448** | **3.81-9.85** |
| **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 | (2947)-(1378) | (27.12)-(12.68) |
| | **Totals** | **(2209)-334** | **(20.31)-3.07** |
| **Energy Absorbing Mirrors** | Change in Technology Costs | 49-71 | 0.52-0.75 |
| | Change in Implementation Costs | 0 | 0 |
| | Change in Operational Costs | 43-64 | 0.45-0.67 |
| | Change in Insurance Claims Costs | (90)-(48) | (0.94)-(0.51) |
| | **Totals** | **2-87** | **0.02-0.92** |

**Table 46: Estimated changes in costs per bus (NPV) and total fleet costs (NPV) over the 12-year analysis period (2019-2031) for the retrofit VRU frontal crashworthiness [VCW] safety measure solutions (cost reductions are shown in (parentheses))**

| Safety Measure Solution | Cost Description | Cost (NPV) per bus (£) | Total Cost (NPV) (£M) |
|---|---|---|---|
| **Class II Mirror CMS Replacement** | Change in Technology Costs | 567-1134 | 6.17-12.33 |
| | Change in Implementation Costs | 378-907 | 4.11-9.87 |
| | Change in Operational Costs | 449-1258 | 4.88-13.68 |
| | Change in Insurance Claims Costs | (5148)-(2419) | (55.97)-(26.31) |
| | **Totals** | **(3753)-880** | **(40.81)-(9.57)** |
| **Energy Absorbing Mirrors** | Change in Technology Costs | 64-91 | 0.69-0.99 |
| | Change in Implementation Costs | 46-55 | 0.50-0.59 |
| | Change in Operational Costs | 73-110 | 0.80-1.20 |
| | Change in Insurance Claims Costs | (206)-(111) | (2.24)-(1.21) |
| | **Totals** | **(23)-145** | **(0.25)-1.57** |

When considering the expected changes in implementation and installation costs associated with the VRU frontal crashworthiness safety measures 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 calculated from the combination of the times taken to install the systems with the cost per hour of performing this task. 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. 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 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 (see Table 45 and Table 46).

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. The changes in operational costs for the minimum geometric requirements, enhanced geometric requirements, energy absorbing structures and windscreen wiper repositioning safety measures were assumed to be negligible due to no material change in the number or value of components used. The increase in operational costs associated with energy absorbing mirrors was associated with replacing these more expensive mirrors when damage by a mirror strike, whilst the Class II CMS replacement solution was assumed to have increased maintenance costs associated with the system. These costs were then used to estimate the net present value (NPV) change in operational costs per fitted bus and the total costs for the whole fleet for the 2019-2031 analysis period (see Table 45 and Table 46).

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. Changes in costs of insurance claims are highlighted below in Table 45 and Table 46.

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.

## 8.6 Cost-benefit analysis outcomes

Table 47 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 VRU frontal crashworthiness safety measure solution. Positive benefit-cost ratios are highlighted in green and marginal benefit-cost ratios in orange. Where 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 47: 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 Geometric Requirements** | New-build | 857-1208 | 2019-2020 | **291.00-ROI** |
| | Retrofit | N/A | N/A | **N/A** |
| **Enhanced Geometric Requirements** | New-build | 8184-10978 | 2022-2022 | **18.03-ROI** |
| | Retrofit | N/A | N/A | **N/A** |
| **Repositioning of Windscreen Wipers** | New-build | 644-716 | 2019-2019 | **ROI** |
| | Retrofit | N/A | N/A | **N/A** |
| **Energy Absorbing Structures** | New-build | 3379-3754 | 2023-2025 | **2.33-6.71** |
| | Retrofit | N/A | N/A | **N/A** |
| **Deployable Run-Over Guards** | New-build | 3379-3754 | 2023-2025 | **2.33-6.71** |
| | Retrofit | N/A | N/A | **N/A** |
| **Class II Mirror CMS Replacement** | New-build | 2947-3274 | 2020-2023 | **8.82-ROI** |
| | Retrofit | 4473-4970 | 2022-2026 | **5.08-ROI** |
| **Energy Absorbing Mirrors** | New-build | 380-601 | 2021-2020 | **4.35-288.24** |
| | Retrofit | 637-1006 | 2021-2023 | **4.39-ROI** |

From this it is clear that all the proposed solutions are likely to be cost-beneficial. This is primarily due to the assumption that these requirements would be implemented during the design of a new-build bus model, thus the costs would be absorbed by the normal research, development and manufacture costs associated with the development of a new bus model. The selection of which safety measure should be taken forward should therefore be based on the feasibility of the solution from the technical feasibility and policy point of view. Deployable run-over guards, although shown to be highly effective in other industries, have not yet been translated to, and proved out for, the bus industry. The replacement of Class II mirrors with CMS would also conflict with the requirements for energy absorbing mirrors. As the Class II CMS system would result in greater savings, it is therefore recommended that the Class II mirror CMS replacement safety measure is adopted over the energy absorbing mirror safety measure.

# 9 Summary of Conclusions and Next Steps

## 9.1 Summary of Conclusions

The cost-effectiveness of several proposed solutions were assessed for the Vulnerable Road User (VRU) Frontal Crashworthiness (VCW) safety measure throughout this project. A range of solutions for redesigning the front end of buses to improve the outcomes of collisions with pedestrians and cyclists were investigated for four key functions including; enhanced Front End Designs (FED), VRU Impact Protection (VIP), VRU Run-over Protection (VRP) and Mirror Strikes (MST). 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, whilst the cost-effectiveness and casualty saving benefits of each solution were calculated. These results were then used to finalise the below final list of VCW safety measure solutions recommended for implementation in the Bus Vehicle Specification:

- Minimum bus front end geometry requirement
- Enhanced bus front end geometry requirement
- Repositioning of windscreen wipers requirement
- Energy absorbing bus front end structures requirement
- Requirement to replace the Class II mirrors with a Class II camera monitor system

Through the process presented in this report, several proposed solutions were not selected for inclusion in the Bus Vehicle Specification. As all investigated solutions were found to be cost-effective, these exclusions were primarily based on the feasibility of the solution from the technical feasibility and policy points of view. Deployable/mechanical run-over guards, although shown to be highly effective in other industries, have not yet been translated to, or proved out for, the bus industry. The replacement of Class II mirrors with CMS would also conflict with requirements for energy absorbing mirrors. As the Class II CMS system would result in greater savings, it is recommended that the Class II mirror CMS replacement safety measure is adopted over the energy absorbing mirror safety measure. Finally, as the current Bus Vehicle Specification already requires yellow mirror housing, it was decided that there was no need to continue to investigate improvements to the visual conspicuity of mirrors.

The Bus Vehicle Specification requirements for each recommended safety measure solution are based on the research presented within 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 current test and assessment procedures to establish the performance of the solution against the proposed specifications. The objectives of the requirements of each proposed solution are shown overleaf.

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.

### Minimum and Enhanced Bus Front End Geometry Requirements

Changes to the front end design of a bus can help to deflect pedestrians out of the path of a bus or scoop them up and along, instead of pushing them down towards the ground. Shape changes for bus front ends were therefore investigated through innovative research using computer simulations that showed that raked (sloped) and curved bus front ends reduced both head injury and run-over risks. As a result, the BSS will specify horizontal curvature and raking requirements. These combine to create a design envelope that aims to deflect VRUs laterally and upwards away from the bus to reduce injury and run-over risk. As some of TfL's bus fleet already have these features, a set of minimum requirements will be adopted in the BSS for new-build buses. As future bus front end ends can be more ambitious in their design, it is proposed that a set of enhanced requirements will be adopted by the BSS for new buses from 2024.

### Energy Absorbing Bus Front End Structures

When collisions between a bus and pedestrian occur, there is often an impact between the bus and the head of the pedestrian. It is possible to reduce the accelerations experienced by the head, and thus the risk of head injuries, through the use of energy absorbing materials, avoiding hard points under the front panels in the design stage or even by altering the front end design of the bus. The BSS, through standardised testing and assessment protocols, sets minimum head impact performance requirements to ensure the accelerations experienced by the head during collisions do not exceed specified injury criteria.

### Windscreen Wiper Protection

The windscreen wipers can have a significant effect on pedestrian injuries, should a collision occur between the pedestrian and windscreen wipers. The wiper mount points are hard and can potentially cause severe injuries as they do not absorb the energy of the impact. Two potential solutions exist, depending on the bus styling and wiper sweep. First, is moving the mount points up to the top of the screen and out of likely impact range. If this is not feasible, a second option is for manufacturers to provide evidence that an energy absorbing covering for wipers mounted below the windscreen has been fitted and is effective. Evidence will be required by additional tests against the windscreen mounts performed according to the test and assessment protocols adopted for evaluating the performance of energy absorbing bus front end structures.

### Replacement of Class II mirrors with Class II CMS

Camera Monitor Systems (CMS) are now entering the market for buses, with these systems replacing the Class II wing mirrors with cameras that provide the same field of view. Images are shown on a monitor that is mounted inside the bus in a similar place to the wing mirror, e.g. on, or in-line with, the A-pillar. These systems have the advantage of removing the wing mirrors, which removes the risk of mirror strike injuries to pedestrians and other road users. The BSS will require CMS to be fitted, but some further research is needed to define exactly how these should be implemented on buses to ensure a suitable cab layout that does not over-burden the driver with information.

## 9.2 Next Steps

Each of the proposed safety measure solutions requires further research to compliment and refine the relevant Bus Vehicle Specifications. The following paragraphs therefore provide an overview of the future steps proposed by this project for each safety measure solution.

The minimum and enhanced bus front end geometry requirements would benefit from an improvement in the biofidelity of the models, an investigation of the potential for changes in leg injury risk and even further investigation into the risks of injury associated with cyclists, 5$^{th}$ percentile females and different VRU travel speeds/gaits. Greater granularity in the variables investigated outside of the design limits would also provide further detail on the safety performance of highly raked and curved bus front end design geometries. These additional investigations could all be integrated into future versions of the bus front end geometry performance tool to refine the generalisability of the injury prediction model to cover the entire range of potential collision characteristics that could be expected in London. Finally, the impact of these changes in bus front end design on bus operations and bus driver safety should also be explored with manufacturers and operators in greater depth.

The limitations of the evidence base that underpins the test and assessment requirements for the energy absorbing bus front end structures include the investigation of a small range of test samples, impact points and impact speeds. Further investigations of these variables are recommended, with a specific focus on how the safety performances of different bus front end designs vary between bus models both from a geometric and material properties point of view. This can be performed through computational simulations, combined with physical tests for validation of the computational simulations. This will reduce the costs of purchasing the bus front end structures and glazing required to perform the physical testing. As the glazed areas of the bus front end are the key component to focus on in regards to providing better pedestrian impact protection, future research and development is required to further develop innovations in windscreen glazing design to determine whether future ambitious safety performance requirements are feasible.

As the current London bus fleet adopts a range of windscreen wiper mounting positions and, as impact protection components are not currently provided for wiper mounts positioned below the windscreen, it is unknown what improvements in injury risk may be provided by better impact protection around the wiper mount. This should be explored through physical testing and computational simulations to determine both baseline impact performance and the impact performance of future protective coverings.

Whilst this research establishes the effectiveness of replacing the Class II wing mirrors with an equivalent Camera Monitor System, it made a number of 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 acceptable levels through image distortion, stitching and partitioning. It is therefore recommended that an investigation of the current state-of-the-art is required to supplement current recommendations.

Finally, whilst deployable run-over protection devices were not considered in this version of the Bus Vehicle Specification, they present a potentially important safety solution for one of the more severe collision mechanisms. Future innovative designs, such as the Bombardier BodyGuard™ system, from bus manufacturers may be developed to help prevent run-overs. This might include a mechanical or airbag device located under the bus that is only dropped down on contact with a pedestrian. Future work will be required to assess the relative run-over prevention performance of such devices, including deployment time, effectiveness and false positive/negative rates.

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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 3)

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 4)

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 5)

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 6)

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 7)

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 8)

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+.

# The Transport for London Bus Safety Standard: Vulnerable Road User (VRU) Frontal Crashworthiness


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, day time 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.

The cost-effectiveness of several proposed solutions were assessed for the Vulnerable Road User (VRU) Frontal Crashworthiness (VCW) safety measure throughout this project. A range of solutions for redesigning the front end of buses to improve the outcomes of collisions with pedestrians and cyclists were investigated for four key functions including; enhanced Front End Designs (FED), VRU Impact Protection (VIP), VRU Run-over Protection (VRP) and Mirror Strikes (MST). The technical feasibility, target population, effectiveness, fleet fitment rate and costs for implementing each safety measure solution as a requirement of the Bus Vehicle Specification were established, whilst the cost-effectiveness and casualty saving benefits of each solution were calculated. These results were then used to finalise the below list of VCW safety measure solutions recommended for implementation in the Bus Vehicle Specification:

- Minimum bus front end geometry requirement
- Enhanced bus front end geometry requirement
- Repositioning of windscreen wipers requirement
- Energy absorbing bus front end structures requirement
- Replacement of Class II mirrors with a Class II camera monitor system


## Other titles from this subject area

**PPR872** Bus Safety Standard: Executive Summary. TfL & TRL. 2018

**PPR819** Analysis of bus collisions and identification of countermeasures. Edwards et al. 2018


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