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The Transport for London Bus Safety Standard: Advanced Emergency Braking (AEB)

Evaluation of Safety Measure

Iain Knight, Martin Dodd, Alix Edwards, Mervyn Edwards, Phil Martin and Mike McCarthy

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This report has been amended and issued as follows:

Version	Date	Description	Editor	Technical Reviewer
1.1	28/07/2022	Corrections to Table 1 Added reference to TfL for latest specification in the executive summary and recommendations	AE	PSM & DH

Executive summary

Bus Safety Standard (BSS)

The 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.

Advanced Emergency Braking (AEB)

AEB is a Driver Assist system, intended to help the driver to avoid or mitigate the severity of collisions. It is also often referred to as Automated or Autonomous Emergency Braking.

AEB uses forward looking sensors to detect the likelihood of a collision. When an imminent collision is identified, and the driver has not acted to prevent it, then brakes are automatically applied to help avoid the collision or minimise its severity. Systems are available that respond in front-to-rear collisions with other vehicles, collisions with pedestrians or cyclists crossing or walking along the road and, at least for passenger cars, where vehicles turn across the path of other vehicles at junctions.

In London, around two-thirds of those killed in collisions involving a bus are pedestrians and most of these are killed crossing the road. The time between the pedestrian first being recognisable as a collision threat and the moment of impact is usually less than 2 seconds. Human drivers have limited opportunity to avoid such collisions but AEB can react more quickly, which could prevent up to around 25% of pedestrian fatalities. Benefits were also identified in less severe front-to-rear collisions with cars and buses, and there was some benefit for cyclists struck from behind by a bus.

Although AEB has become commonplace in new cars and trucks, city buses pose a unique additional challenge. Bus operations already generate a significant quantity of non-collision injuries because passengers fall during normal operation. This includes when standing, passengers, or seated-but-unrestrained passengers, fall during braking. The research has confirmed that AEB has the potential to exacerbate this, though the risk comes almost exclusively from the potential for false positive AEB activations rather than instances when the system genuinely acts to prevent a collision. Thus, the rate of such false activations is very important to the size of the overall benefit.

Analysis of this potential trade-off showed that a system allowing maximum bus deceleration would give the best outcome in terms of fatality reduction, provided it suffered less than one false activation every 600,000 km. It would still offer a substantial net monetised benefit when an increase in slightly injured casualties was considered against the reduction in fatalities.

The analysis suggested that the risks to bus occupants could be mitigated by capping the maximum deceleration to 7 m/s^2. However, this assumes the risk to bus passengers is related only to peak deceleration. Laboratory data suggests the brake 'jerk' (rate of change of deceleration) is also an important factor in determining the likelihood of a fall. This could not be evaluated in the available data and might increase if peak deceleration were to be capped.

Specifications and test protocols have been written that define what is meant by AEB and allow objective measurement of AEB performance in terms of both true and false positive activations. The main focus is objective and repeatable track tests but requirements for systems to record activation details for monitoring/liability purposes and for the provision of manufacturer evidence that false positive activation requirements will be met in service.

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1 Introduction to the Bus Safety Standard (BSS)

1.1 The BSS

In 2018 the Mayor of London, Sadiq Khan, set out a 'Vision Zero' approach to road casualties in his transport strategy (Transport for London (TfL), 2018). It aims for no one to be killed in, or by, a London bus by 2030 and for deaths and serious injuries from road collisions to be eliminated from London's streets by 2041.

Transport for London (TfL) commissioned the Transport Research Laboratory (TRL) to deliver a programme of research to develop a BSS as one part of its activities to reduce bus casualties. The goal of the BSS is to reduce casualties on London's buses in line with the Mayor of London's Vision Zero approach to road safety. The BSS is the standard for vehicle design and system performance with a focus on safety. The whole programme of work includes evaluation of solutions, test protocol development and peer-reviewed amendments of the Bus Vehicle Specification, including guidance notes for each of the safety measures proposed by TfL. In parallel to the detailed cycle of work for each measure, the roadmap was under continuous development alongside a detailed cost-benefit analysis and on-going industry engagement. The BSS programme is illustrated below in Figure 1.

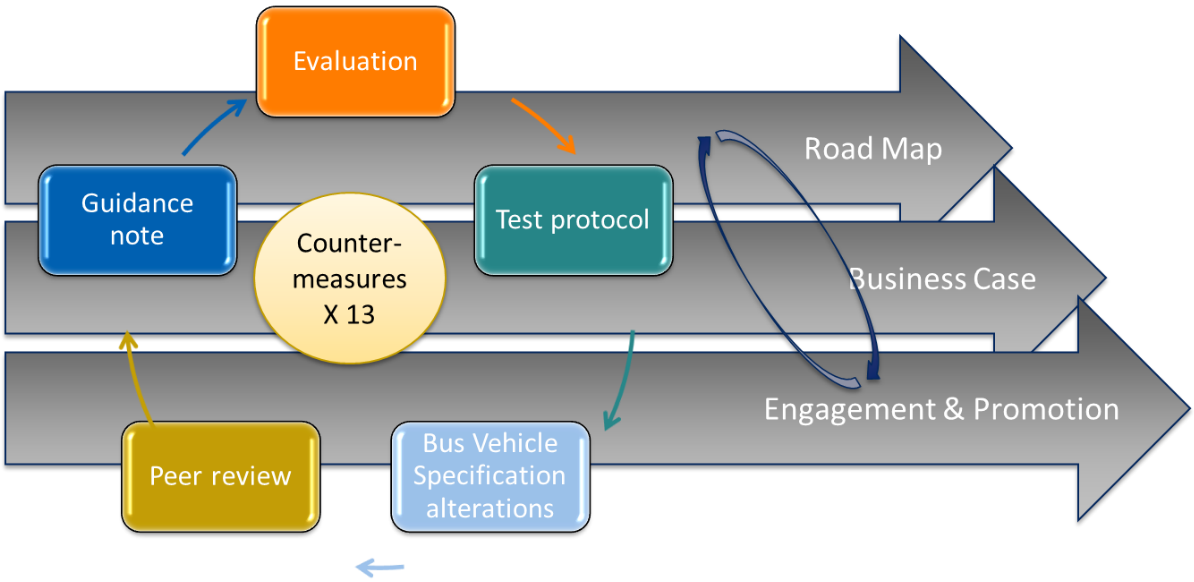


Figure 1: Summary of the BSS research programme

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

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

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

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

1.2 Bus safety measures

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

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

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

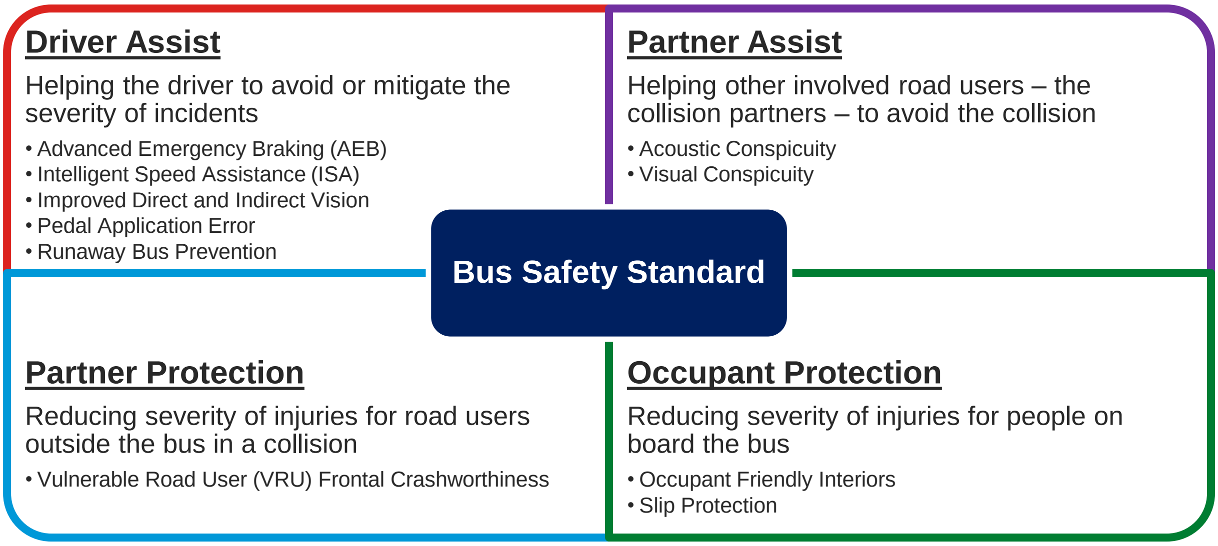


Figure 2: Bus safety measures

1.3 Advanced Emergency Braking (AEB)

The focus of this report is on AEB, which is a driver assist system designed to help the drivers to avoid incidents. AEB systems use forward looking sensors to detect the likelihood of a collision. When it identifies that a collision is imminent, and the driver has not acted to prevent it, then the system will automatically apply the brakes to help avoid the collision, or at least to minimise its severity. Systems are available that respond in front-to-rear collisions with other vehicles, collisions with pedestrians or cyclists crossing, or walking along the road and, at least for passenger cars, where vehicles turn across the path of other vehicles at junctions.

2 Defining the problem that AEB is intended to mitigate

2.1 Casualty priorities for TfL

TfL's aim in implementing the BSS is to assist in achieving 'vision zero' on the principle that no loss of life is acceptable or inevitable. Thus, the largest focus is on incidents resulting in death or serious injury. However, TfL recognise the disruption and cost that minor collisions can have for bus operators and the travelling public alike. Thus, safety features that can reduce the high frequencies of incidents of damage-only and/or minor injury are also included within the scope. The high-level matrix below in Table 1 categorises and prioritises the casualties based on past data for London derived from the GB National collision database.

Table 1 shows that over the past decade the highest priority casualty group in terms of death and serious injury from collisions involving buses in London has been pedestrians severely injured in collisions where the bus was coded as going ahead, without negotiating a bend, overtaking, starting or stopping, etc.

2.2 The casualty problem for AEB

(Edwards, et al., 2017) studied 48 police fatal collision reports where London buses were involved. The findings were that 37 of these fatalities were pedestrians and 30 of them were killed when simply crossing the road in front of a bus moving at normal traffic speeds. Most involved a collision between the front of a double decker bus and a pedestrian moving from the nearside. Around 60% involved a collision with the nearside or farside 20% of the front of the vehicle, that is the outer edges of the vehicle. The amount of time between the pedestrian first becoming recognisable as an imminent collision risk (i.e. turning to clearly start crossing or emerging from behind an obstruction) was less than 2 seconds in around 87% of cases and less than 1 second in around 67%. In most cases, therefore, a driver exhibiting a normal reaction time in the range of 0.75 to 1.5 seconds would have very little, if any, opportunity to avoid a collision. This short reaction time is a function of the short amount of time it takes a pedestrian to walk from a safe position on the kerb to the position of impact and does not mean the bus was speeding or going too fast for conditions. In most cases the bus was travelling at 25 mile/h or less immediately before the collision situation became apparent.

A broad range of literature supports the conclusion that pedestrians crossing in front of a bus going ahead is the most common cause of death and serious injuries in collisions involving buses, see for example (Knowles, et al., 2012) (Robinson & Chislett, 2010) (Yang, 2007). These studies also found that most collisions occurred in clear weather and well-lit conditions, though (Knowles, et al., 2012) did find a peak in fatalities at night at the weekend, attributed to social activity.

Collisions involving cyclists are a lower priority for both Killed and Seriously Injured (KSI) and minor collisions but remain significant, accounting for 5% of the casualty prevention value for all collisions involving buses.

In terms of KSI, front-to-rear collisions with car occupants are a much lower priority, though they do make up a small proportion of minor collision costs.

However, Table 1 also shows that non-collision injuries to bus occupants are a very close second priority in terms of death and serious injury and by far the highest priority when the large volume of minor injuries is considered. A substantial proportion of those injuries occur when the vehicle is subject to harsh braking, acceleration, or cornering. Avoiding collisions with pedestrians will typically involve high levels of deceleration and, therefore, carries a risk of injury to passengers on board the vehicle. Pedestrian collisions usually involve one individual pedestrian and there can be up to around 100 passengers on a bus, though average bus occupancy in London is around 19[1].

Thus, the problem that AEB is intended to solve is primarily the prevention of pedestrian collisions with the front of a bus through an ability to react faster than a human in a very dynamic collision type. Secondary benefits can be achieved through the prevention of collisions between the front of the bus and cyclists and other vehicles (cars, buses and trucks). These benefits must be achieved without excessively worsening an existing problem with injuries to passengers on board the bus, which in a significant proportion of cases are caused by braking.

Potentially AEB could also be used to mitigate the problem of pedal confusion. That is, if a driver unintentionally applies the accelerator rather than the brakes and the AEB sensors detected a collision then the AEB could override the driver action. This is contradictory to the way most AEB systems currently work. Typically, now they will act only at the last second where the driver does not act because of concern that they are not yet sophisticated enough to over-rule a driver that might see something the system does not. Whilst no systems in the commercial vehicle market were identified that could offer this function, late in the project a system was identified on passenger cars[2]. This used AEB sensors in combination with parking bay markings and observation of the way the accelerator pedal was applied in order to identify a pedal misapplication and disable throttle/apply brakes. Therefore, it is likely that this could be considered in future.

TfL have identified there would be benefit to bus operations if AEB was able to identify imminent bridge strikes or even tree branch strikes. Although such incidents rarely result in casualties, the first has a clear potential for catastrophic collisions and the latter results in a lot of damage cost to operators. Now, no systems are known of that could reliably detect tree branch collisions with the upper deck. In theory, systems could potentially detect bridges. However, anecdotally, bridges and gantries have posed problems for AEB systems. Early systems sometimes suffered false positives because the sensors sometimes saw bridges as a potential vehicle collision, particularly if a gradient on the approach made the bridge deck appear lower than it really was. Another system had a high profile false negative where a large truck was

[1] Based on DfT data for 2016/17; table BUS0304 available from https://www.gov.uk/government/statistics/annual-bus-statistics-year-ending-march-2017

[2] https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/pedal.html

crossing perpendicular to a car equipped with AEB, but the radar sensor classified it as a possible bridge and ignored it.

Thus, these additional functions cannot be confirmed as feasible at this time but are worthy of inclusion in a roadmap of future functionality that TfL would like to see and further exploration with industry.

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

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

Casualty Type	Collision type	Fatal	Serious	Slight	KSI	Total
	Total	4.2%	7.8%	5.0%	6.4%	6.0%
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 Definition of an AEB system

AEB is a system that uses forward looking sensors such as Lidar, Radar, Camera, or combinations of more than one sensor, in order to identify a risk of an imminent collision. It will typically first warn the driver of the risk and, if the driver does not act, then it will apply braking automatically in order to avoid the collision or to reduce the collision speed and therefore the potential for injury. For flat fronted vehicles like buses, ensuring that the vehicle is braking hard at the point of collision can have benefits, in terms of reducing the chance that the pedestrian is subsequently runover, even if the collision speed is not reduced much. Several sub-systems of AEB can be considered, depending on the type of collision they are effective in, for example vehicle front to vehicle rear, pedestrian crossing, vehicle turning across path etc. The types of AEB being considered within the scope of this research are those sensitive to front-to-rear collisions with other vehicles, collisions between the front of a bus moving at significant speed and crossing pedestrians and collisions between the front of a moving bus and cyclists.

4 Existing evidence of system performance

There are different aspects of AEB performance that can be considered. True positive performance is defined as how well the system performs when it is activating in the situations it is intended to activate in. For example, for a pedestrian sensitive AEB system this might be a measure of the maximum speed from which the system can avoid a collision with a pedestrian crossing in front of the vehicle, or the speed reduction achieved when the collision cannot be avoided.

All AEB systems carry a risk that the sensors ‘misjudge’ a traffic situation such that a warning function or even automated braking are applied in a situation where it would not be intended to act. For example, this might include a situation where a pedestrian walked quickly towards the kerb, on a collision course with a bus, took one step off the kerb but then quickly stopped and stepped back onto the kerb. The frequency with which this sort of situation occurs can be considered the performance of the system in terms of false positive activation.

4.1 True positive performance

The authors are not aware of any AEB fitted to city buses and thus, there are no directly comparable existing results available to quantify the true positive performance of bus AEB.

Tests developed for Euro NCAP show a wide range of performance of passenger car systems. For example, (Hulshof, et al., 2013) identified low speed systems that avoided stationary cars ahead from initial travel speeds of up to 30 km/h but did nothing at speeds above this, to systems that could avoid other cars at much higher speeds and reduce impact speed in other configurations. (Knight & Avery, 2015) found that systems for HGVs did the opposite. They did not function at all at low speed (approximately <15 km/h) but would operate at speeds of at least 80 km/h. The best truck system tested could avoid a stationary car in the lane ahead from a speed of 80 km/h and from 90 km/h, the maximum speed of trucks in Europe, the impact speed would be reduced to around 10 km/h.

Similarly, (Grover, et al., 2015) identified that the performance of pedestrian AEB systems on passenger cars ranged from simpler systems that do not fully avoid any collisions but reduce the speed slightly in a wide range of collision configurations, to more sophisticated systems that can fully avoid impact in most of the different scenarios tested (up to travel speeds of 60 km/h). Thus, the question of AEB is not a binary one, of fit or do not fit. There are many different performance variations, each tailored to the specific situations they are used for, and in accordance with the characteristics, price and sophistication of the sensing systems used.

The research reviewed above clearly shows the wide variations in the performances of different AEB systems on the test track and the substantial potential of the high performing systems. This does not always translate to a similar level of effectiveness in terms of casualty reduction in the real world. However, AEB on passenger cars has been the subject of extensive study using rigorous statistical techniques comparing police reported collision rates or insurance claim rates for comparable vehicles with and without the technologies. The results of such studies vary substantially in the magnitude of the benefit estimated, but they are all in agreement that the benefit exists and is strongly positive. For example, (Fildes, et al., 2015) showed a 38% overall reduction in rear end crashes for passenger cars fitted with AEB compared with a control group of similar vehicles. This was based on a meta-analysis of data from a range of countries around the world.

It is harder to measure the effect of pedestrian AEB in the same way because the total number of collisions is much smaller than in vehicle to vehicle rear end situations. However, a range of studies have predicted benefits based on in-depth collision reconstruction and then re-modelling the collision based on what would have happened if the vehicle had been fitted with AEB. One typical example of this approach (Lindman M., 2010) found that an AEB with characteristics based on a Volvo car system capable of avoiding collisions at up to around 35 km/h could prevent 24% of pedestrian fatalities caused in collision with the front of the vehicle.

If benefits of this magnitude can be achieved with city buses, then the dominance of pedestrian collisions on total fatality numbers means that fitment of AEB could be a very significant step in improving the collision record of buses and saving lives.

4.2 False positive performance

For pedestrians, one of the limitations on true positive performance is the fact that pedestrians can change direction quickly combined with the need to avoid false positives. Almost all early systems would not, therefore, activate the brakes until the pedestrian was fully in the path of the vehicle. This leaves only a very short time for braking, which means that they were much less effective in cases where, without AEB, an impact would occur at the outer edge of the vehicle. Test experience and scores in Euro NCAP suggests that this design approach is changing, and brakes are being applied earlier when the pedestrian remains slightly outside the vehicle path. Evolving and improving algorithms and path prediction capability is likely to be the enabler of these changes. However, what constrains the extent of these improvements is the avoidance of false positives. False positive is often used as a ‘catch-all’ term for activations that are unwanted, but this can cover a range of different situations. False positive brake applications are undesirable on any vehicle because they create a risk of a vehicle behind colliding with a vehicle they do not expect to stop suddenly. However, city buses represent a unique challenge in this respect because they may be carrying multiple standing passengers and the seated passengers will not be restrained by a seatbelt. There is ample evidence that many bus occupant injuries occur without external impacts and a significant proportion of those are thought to occur during (driver-applied) braking. It is, therefore, very important to explore the different situations that could be false positives in more detail.

(Lubbe, 2014) reviewed definitions of false positives and cited a basic definition from (Martinez & Martinez, 2008), which is interpreted considering application to AEB below in Table 2

Table 2: Basic classification of system actions; adapted from (Martinez & Martinez, 2008) as cited by (Lubbe, 2014)

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

In the most basic form, then true positives and true negatives are always desirable and false positives or negatives are always undesirable.

However, when considered considering AEB there are several questions that become relevant, for example:

- Can the assessment of whether a collision will happen be a binary yes/no?
- Are false positives always undesirable and true negatives desirable?
- What is meant by system activation?

(Hierlinger, et al., 2017) have defined operational load cases and system activations as follows. Where a collision will occur, then the AEB shall activate subject to its operational boundary characteristics (e.g. max speed etc). Where a collision clearly will not occur, the system must not brake. However, a zone is defined close to the boundary between where a collision will and will not occur if there is no intervention, where the vehicle ***may*** brake. Similarly, in addition to the four categories defined in Table 2, above, (Seiniger, et al., 2014) identify a 'near miss' category and define it as the 'grey zone' between wanted and unwanted system reactions, which depends strongly on the situation and risk awareness of the individual drivers. This is illustrated in Table 3, below.

Table 3: Classification of collision risk and system activation for pedestrian AEB by the ASPECCS project. Source: (Seiniger, et al., 2014)

	Yes	No
Yes	**True Positive (TP)**	**False Negative (FN) - not detected system limits**
No	**Near Miss (NM)** **False Positive (FP)**	**True Negative (TN) - correct no intervention**

In this context, a near miss could also potentially be considered a premature positive rather than a false positive. That is, a traffic situation is evolving that represents a clear collision risk, but the system intervenes at a time when the driver considers that he or she is already aware of the risk and can comfortably avoid the problem without assistance by braking, or steering, or sometimes without intervention. For example, it may be that the driver can see that the other vehicle is going to steer out of their path before collision because it is indicating left and slowing ahead of a left turn. In this situation, the gap is decreasing but the driver estimates the left turn will be complete before the gap is excessively reduced. The AEB does not know the vehicle will turn left.

Whether any individual driver considers an intervention premature will depend on their own individual driving characteristics. An aggressive driver who regularly brakes harshly and is used to avoiding hazards relatively late, will have a different interpretation of what is premature to an overly cautious driver who rarely brakes hard and typically maintains large gaps to vehicles. Similarly, there is a wide range in human emergency braking performance. For example, (Dodd & Knight, 2007) reported on a driving simulator trial with a group of normal drivers. The simulated vehicle was capable of a deceleration of 10 m/s^2, but in emergency events on average the subjects only achieved mean decelerations of 7.5 m/s^2 with a standard deviation of 10%. On average, drivers took 0.93 seconds from first touching the brake to achieving 90% of their peak deceleration. In this measure the standard deviation was 35% of the mean. This means that some drivers will need to brake earlier than others in order to avoid a collision in the same situation. Once braking some drivers will need a much higher peak brake force to avoid collision because they took longer to reach it, which will affect their perception of how severe an emergency was.

This variation in driver perception leads to the consideration of whether a classically defined false positive is always undesirable. (Lubbe, 2014) cites (Kallhammer, 2011) who argues that activations should be assessed in terms of their usefulness, not in terms of true and false. (Kallhammer, 2011) argues that if a true positive alarm is technically very accurate, it will be very rare because collisions are very rare. Drivers with no experience of such a rare event will not have learned how to react efficiently to it, such that the alert will have no value. (Abe & Richardson, 2006) also studied the timing of forward collision warnings and found that alarms that were activated after the driver had already initiated braking were considered late and that typically drivers expected alarms to be activated before they instigated braking. The authors found that when this does not happen, driver trust in the system is substantially decreased. This means that a true negative that is highly technically accurate (not activating unless a collision is certain in the absence of system intervention) can also be undesirable and undermine trust in the system.

What was clear from the research was that if an intervention was made, then the driver must be able to identify a clear situation representing a ‘risk of collision’. Alerts issued when no identifiable risk is present are clearly false and undesirable.

These factors in combination led (Lubbe, 2014) to propose the following classification system in Figure 3.

System activation			
Yes	No		
True Positive (TP)	False Negative (FN)	Yes	Collision certain without system activation?
Desired False positive (DFP)	Desired True Negative (DTN)	No	
Undesired False positive (UFP)	Undesired True Negative (UTN)		

Figure 3: Enhanced Activation classification proposed by (Lubbe, 2014)

The definition of (Lubbe, 2014), above, is based predominantly on systems where activation means a collision warning, or alert. Typically, an AEB system will have a minimum of two degrees of activation: warning followed by a brake intervention. However, in some systems, the warnings may be staged, for example, visual only, followed by visual and audible and the automated braking may also be staged, starting with moderate braking and progressing to full braking later. Some systems may also use a short duration brake 'pulse' as a tactile warning. It is hard to imagine any truly false positive braking application, with the possible exception of a warning pulse, as 'desired'. (Lubbe, 2014) acknowledges this and states that direct consideration of different types of activation within the matrix would be complicated and prefers that the matrix is repeated for each different type of activation.

True positives are always desirable and false negatives are always undesirable. However, the boundary between desirable and undesirable false positives and true negatives is likely to vary depending on the type of activation. (Kallhammer, 2011) based his conclusions on consideration of the usefulness of collision alerts in helping the driver to learn how to respond to them. (Knight, et al., Forthcoming) reviewed the urgency and criticality of warning and how these concepts were dealt with in international standards. It was found that three levels of warning priority can be identified (UNECE WP.29., 2011):

- **Low-level**: driver prepares action or decision within 10 seconds to 2 minutes; may escalate to a higher level if not acted upon;
- **Mid-level**: requires action or decision within around 2 to 10 seconds; may escalate to high-level warning if not acted upon;
- **High-level**: warning requires the driver to take immediate action or decision (0 to around 2 seconds) to avoid a potential crash that could result in serious injuries or fatalities.

Under this classification, it is highly likely that most warnings issued by AEB systems would be considered as high-level ones, though it is possible that in more slowly developing situations such as collisions with a slower moving vehicle ahead, a staged approach may be possible. For example, some mid-level warnings could potentially be used at an early stage of collision probability and low-level warnings could be applied to discourage drivers from following too close.

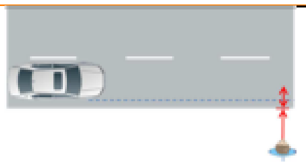
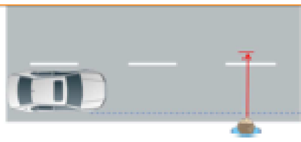
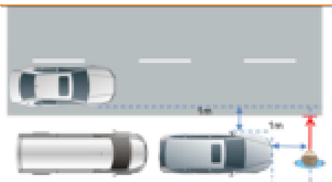
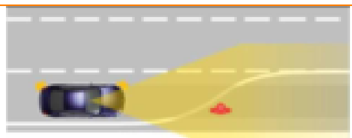
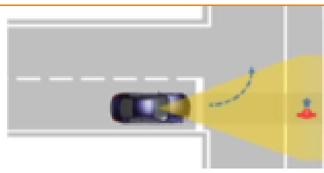
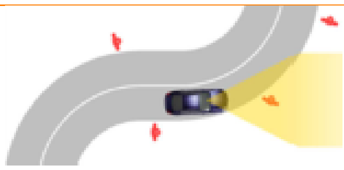
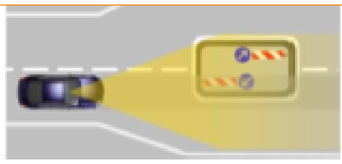
It is more difficult to see how a technically 'false' brake application would be useful. However, there is still some room for interpretation here as to what is 'false'. The definition used by (Lubbe, 2014) is *'when the collision is certain to occur if the system does not intervene'*. However, whether the collision is certain depends to an extent on the performance of the individual driver. This could be interpreted as if the best human driver hit the brakes this instant and achieved maximum deceleration on the best available surface. Alternatively, it could be considered as an average or even worst-case driver hitting the brakes more slowly and achieving lower deceleration. At higher speeds, then the latest driver action capable of avoiding a collision can be steering. The moment of last avoidance by steering may be a considerable time after the moment of last avoidance by braking. This will vary by vehicle type because the ability to quickly swerve whilst remaining safe and stable will be different in a passenger car, bus and fully laden heavy goods vehicle for example. Thus, the definition of 'false' is open to a significant degree of interpretation.

The potential for different levels of warning and different levels of braking have been considered. However, when false positives are considered, it is also possible that different durations of braking could be considered. For example, if an unusual sequence of images fools a camera sensor into thinking a collision is imminent it might cause a false braking activation. However, the sensor input may change very quickly to reveal the true situation, in which case the brake demand may be immediately removed such that the brake application was only short. This would clearly create considerably less speed change than a full emergency stop. In the case of vehicles with pneumatic brake systems, it may also imply lower peak deceleration because such brake systems can have a relatively slow response time.

Thus, an AEB generating a false positive brake demand that was only applied for 0.15 seconds might not generate much acceleration at all because the demand would be removed before pressure had significantly built in the brake chambers.

In the development of a proposal for tests to evaluate the performance of AEB, the ASPECCS project (Seiniger, et al., 2014) attempted to identify a range of pedestrian traffic situations that they considered had a high potential for false positives. This is reproduced in Table 4, below.

Table 4: Some pedestrian traffic scenarios considered likely to cause false positive activations. Source: (Seiniger, et al., 2014)

Scenario		Illustration
1	Pedestrian walks towards the driving corridor as if to cross but stops before entering the path of the vehicle	
2	Pedestrian walks into the path of the vehicle but then steps back again	
3	Pedestrian stands next to driving corridor and accelerates to run across the street such that they would clear the path of the vehicle before impact	
4	Running child emerging from behind an obstruction stops before entering the path of the vehicle	
5	Pedestrian on the kerb ahead of a closing slip lane, layby or bus stop as the vehicle accelerates forward and out into traffic	
6	Pedestrian on kerb opposite an emerging vehicle at a junction	
7	Pedestrians on kerb as vehicle negotiates a bend such that pedestrian appears in the path of the vehicle until steering wheel is turned	
8	Pedestrians on a central traffic island that requires the vehicle to steer around it	
9	Multiple target scenario – for example a group of people standing close to the vehicle path and one person starts crossing	

Although all these situations were classed by (Seiniger, et al., 2014) as carrying a high possibility of false activation, it is possible to review them considering the classifications reviewed previously. Firstly, it is apparent that a pedestrian is present in every scenario considered. Thus, there is no test of the most unhelpful false positive, where the driver would not recognise any feature of the driving scenario as representing a risk the system was responding to. Scenarios 1 to 4 can be considered to be ‘near miss’ situations where a pedestrian stops suddenly just before entering the path, enters the path and quickly pulls back, or enters the path then recognises the threat and runs forward such that they move out of the path of the vehicle at the far side before a collision occurs. These can be considered to be exploring the boundary between the desirable and undesirable false positives in the matrix proposed by (Lubbe, 2014). The timing of these situations and consideration of how human drivers would respond is critical to consideration of whether or not the activation is ‘false’.

If the pedestrian action (stopping, backing up or accelerating) occurs the minimum possible time before collision, then the research suggests an activation, even braking, would be warranted because the driver would see the risk and understand why the system had acted. Indeed, it is possible or even likely that many human drivers would react in a similar way. The key with respect to consequences, might be the extent of the braking reaction – that is, how quickly does the system recognise that pedestrian action has averted the collision and deactivate the automated braking.

If the pedestrian action occurs a longer time before collision and the system reacts then it may be considered a premature activation. The driver may still see the threat and understand why the system has reacted but if that reaction has come at a time the driver thinks is too early, the research suggests it will undermine trust in the system.

Scenarios 5 to 8 are all situations where the system activates whilst avoidance of the collision by steering remains possible. In these situations, the reason for the intervention would still be likely to be apparent to the driver, who would see that for a moment at least a pedestrian was directly in the path of the vehicle. However, the driver is less likely to identify them as risky situations because the pedestrian may be stationary on a traffic island or walking along a pedestrian pavement, not imminently entering the road. Therefore, arguably, drivers may find such interventions less useful and more damaging to trust in the system.

Finally, scenario 9 could more accurately be described as a true positive (or false negative) test. In this scenario, one person from among a crowd of stationary people, crosses the road but may be difficult to identify because of the proximity of the other people. This is a hazardous situation that human driver and sensors alike may find difficult to deal with and where a system activation would be very useful. It may also be a particularly useful capability in London where pedestrian volumes are high.

Consideration of true and false positives, as defined by the literature is complex. However, it is also very sensitive and creates issues of liability which means that manufacturers are unlikely to publish data on how often they expect false positives of any type to occur. To generate a reliable estimate of a high performing system is liable to take millions of kilometres of real-world driving. Undertaking an independent trial to establish typical false positive rates would be very expensive and time consuming. Thus, no literature has been found publicly quantifying false positive rates of any production AEB system fitted to any vehicle type.

4.3 Summary

In summary, AEB that acts in vehicle front to vehicle rear collisions has been proven to be highly effective when fitted to passenger cars. Systems that act in pedestrian collisions are predicted to be very effective.

Fitment of systems acting in collisions with the rear of the vehicle ahead is high on both passenger car, HGV and coach models of recent years.

No evidence related to a pedestrian sensitive AEB system on city buses was identified and it is thought likely that no such system is yet in service.

Consideration of the potential adverse effects of false positives is complex and at least partly dependent on interpretation relative to the broad spectrum of driving behaviour that might be considered ‘normal’ across the population. No published data was identified that quantified any actual observed frequency of false positive activation either in test conditions or in normal service.

5 Testing true positive performance

5.1 Methods

Given the lack of existing information about the likely performance of AEB fitted to buses, particularly with an emphasis on pedestrian functionality, independent testing of a system was considered necessary. One manufacturer made a prototype system available for this work. It was, therefore, necessary to consider how it should be tested, so existing test protocols for other AEB systems and vehicle types, namely passenger cars, were reviewed. The relevant standards considered were:

- UNECE Regulation 131 / EU regulation 347/2012/EC
- Euro NCAP test protocol for AEB car-to-car
- Euro NCAP test protocol for AEB VRU
- NHTSA test track evaluations for AEB
- IIHS AEB test protocol

When considering each of these test procedures for the purposes of initial evaluation of AEB as a countermeasure for buses, only the scope of the test procedure and how this related to the brief from TfL and the collision data for buses in London were considered.

The outline scope of what each existing protocol is intended to measure is shown in Table 5 below, where a field shaded green shows that a test type / configuration is included and a field shaded in red shows that it is not.

Table 5: AEB functions/tests covered by different existing test protocols

	Test type		Test protocol: Trucks & buses – EU regulation 347/2012	Cars – Euro NCAP 2014	Cars – Euro NCAP 2016	Cars – Euro NCAP 2018	Cars – US NCAP	Cars – IIHS 2013
True positive	FCW & dynamic brake support							
	AEB front to rear	Stationary						
		Moving						
		Braking						
	AEB pedestrian	Crossing						
		Longitudinal						
		Night-time						
	AEB cyclist	Crossing						
		Longitudinal						
False positive	Flat steel plate							
	Drive between two stationary vehicles							

TfL's brief for this project was to consider AEB that works for pedestrians, car occupants and cyclists. The only existing test protocol covering all three of those is the Euro NCAP 2018 protocol so this was selected as the basis for the evaluation testing. The tests included in the protocols are described in more detail below:

- Car-to-car-rear stationary (CCRs): A car driven at the rear of a stationary car target, at initial speeds of 10 to 50 km/h (30-80 km/h for forward collision warning and dynamic brake support) at a range of different lateral offsets from the target car.
- Car-to-car-rear moving (CCRm): A car driven at the rear of a car target moving at 20 km/h. The initial speed of the impacting car is between 30 and 80 km/h and a range of lateral offsets are considered.
- Car-to-car-rear braking (CCRb): A car following another car at a constant speed of 50 km/h at a distance of 12m or 40m when the lead car brakes with a deceleration of 2 or 6 m/s^2.
- Car-To-Pedestrian Farside Adult: vehicle travels forwards towards an adult pedestrian crossing its path, moving quickly (8 km/h) from the far side of the road. Nominal impact point is set such that the pedestrian crosses 50% of the vehicle width before impact, assuming no braking takes place.
- Car-to-Pedestrian Nearside Adult: vehicle travels forwards towards an adult pedestrian crossing its path moving at average speed (5 km/h) from the nearside. Nominal impact points at 25% or 75% of vehicle width.

- Car-to-Pedestrian Nearside Child: vehicle travels forwards towards a child pedestrian crossing its path from the nearside and moving quickly (5 km/h) from behind an obstruction. Nominal impact point 50% of vehicle width.
- Car-to-Pedestrian Longitudinal Adult: vehicle travels forwards towards an adult pedestrian walking in the same direction in front of the vehicle; Alignment is at 25% or 50% of the width of the vehicle.
- Car-to-Bicyclist Nearside Adult: vehicle travels forwards (20-60 km/h) towards a bicyclist crossing its path cycling at 15 km/h from the nearside such that in the absence of braking impact would occur at 50% of car width.
- Car-to-Bicyclist Longitudinal Adult: vehicle travels forwards (25 to 60 km/h) towards a bicyclist cycling (15 to 20 km/h) in the same direction in front of the vehicle.

Passenger car-to-pedestrian tests for AEB are performed at speeds ranging from 20-60km/h (50-80km/h for FCW), in ambient conditions representing both day and night.

It should be noted that Euro NCAP is a consumer information scheme, so it does not require that the AEB fully avoids a collision in each and every test. Points are awarded for the level of performance achieved in each test and in some cases (crossing pedestrian tests from vehicle speeds in excess of 40 km/h) maximum points are achieved just for reducing speed to a defined lower level. Thus, a five star car will not avoid in every case and impact will still occur in certain circumstances.

The pattern of collisions experienced by buses in London is different to that experienced by passenger cars across Europe. The existing test procedures have been designed for European passenger cars and not all tests relate to mechanisms frequently experienced by London buses. (Edwards, et al., 2017) shows that pedestrian collisions are the highest priority collisions for buses in London. Analysis of collision data highlighted that night-time collisions with pedestrians were significant (c.40% of fatalities) and that almost all cases occurred in areas lit by streetlights. No fatalities were recorded in STATS19 where a pedestrian was walking along the carriageway when hit by a bus. Thus, all pedestrian tests except longitudinal were included.

Cyclist collisions were of much lower priority than pedestrians but were still significant. However, the vehicle manufacturer reported that less development effort had been put into the cyclist part of the system at the time of testing. So, a small selection of cyclist tests was included.

Collisions with cars were the lowest priority and most bus collisions in London tend to be relatively low speed, with buses mostly travelling at 50 km/h or less. Conversely, the tests involving collisions with moving vehicles ahead are amongst the most complex and time consuming of the AEB tests. Thus, only consideration of tests involving a stationary car target were considered at this stage.

The manufacturer of the prototype system had already tested the system according to the earlier Euro NCAP 2016 protocol and provided results to the project team. Thus, in those tests only a sample of the full test matrix was undertaken, with the aim of independently validating the results provided. However, the additional tests in the

2018 protocol had never been tested before by the manufacturer and, therefore, were tested in full, where relevant according to the collision data analysis above. Two rounds of testing were undertaken within this project, one with Horiba Mira and the other with Millbrook Proving Ground.

5.2 Results

It should be noted that the results of a system in prototype form are considered confidential to the manufacturer and their supply chain and could be commercially sensitive. In addition to this, further development and tuning of the system may change the performance before it reaches production. For these reasons, the results have not been presented explicitly in terms of performance in each individual test. The presentation of results is more general to avoid inappropriate inferences or giving away excessive manufacturer IP.

5.2.1 Test performance

Considerable variability in impact position was observed during the tests (see section 5.2.3 for further details). Despite this it was possible to pick selected results that were close to the conditions specified by the protocol. In these cases, the performance of the AEB generally matched that expected by the manufacturers of the system.

Although, for confidentiality reasons of the prototype tested, individual results have not been published, the data show that full avoidance was achieved in some pedestrian crossing cases relatively close to protocol defined impact points, from a test speed of 40 km/h.

Analysis of cyclists crossing the path of the vehicle showed that this prototype version had minimal performance, reducing impact speeds by just a very small percentage. This was attributed to limitations in the width of the sensor field of view and the relatively high speed of the cyclist in this scenario (15 km/h). This is expected to improve over time as wider-angle sensors are developed for the car market.

Performance when approaching a slower moving cyclist in the same lane ahead was good with avoidance at every bus speed tested when the cyclist was aligned with the centre of the bus. There was only slight reduction in performance when the cyclist was aligned with a 25% impact point (nearside quarter) on the bus.

In situations involving potential collision with a stationary car, performance was as expected, avoiding at all test speeds. Some inconsistency was noted in night-time tests without streetlights. Note that the test target does not have tail lights so is not representative of a real vehicle in that situation.

5.2.2 Braking strategies

The braking strategy employed to achieve the observed true positive performance levels varied according to the circumstances. Effectively some collision scenarios are harder to avoid than others and in the harder cases a more aggressive braking strategy was required. In general, low speed collisions with cars in the lane ahead are less severe than pedestrian collisions. Within pedestrian collisions, higher speeds and lower % impact points are more challenging and require more aggressive braking. Acceleration data from a small sample of tests is produced below in Figure 4, Figure 5 and Figure 6 to illustrate the effects.

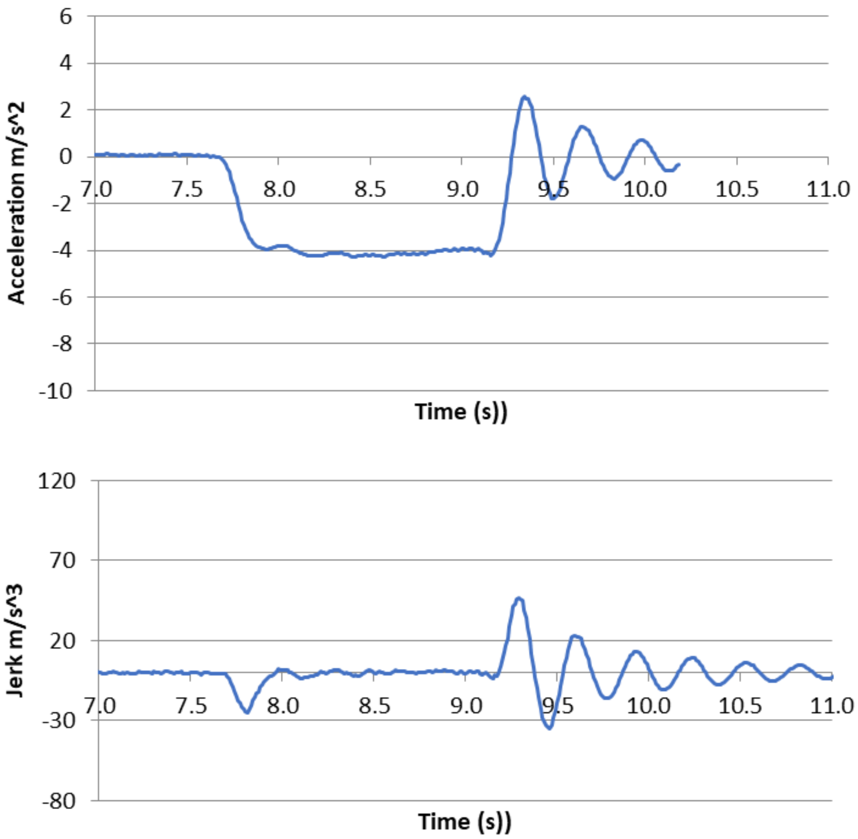


Figure 4: Longitudinal bus acceleration (top) and rate of change of acceleration (bottom): Easy - low speed avoided car collision

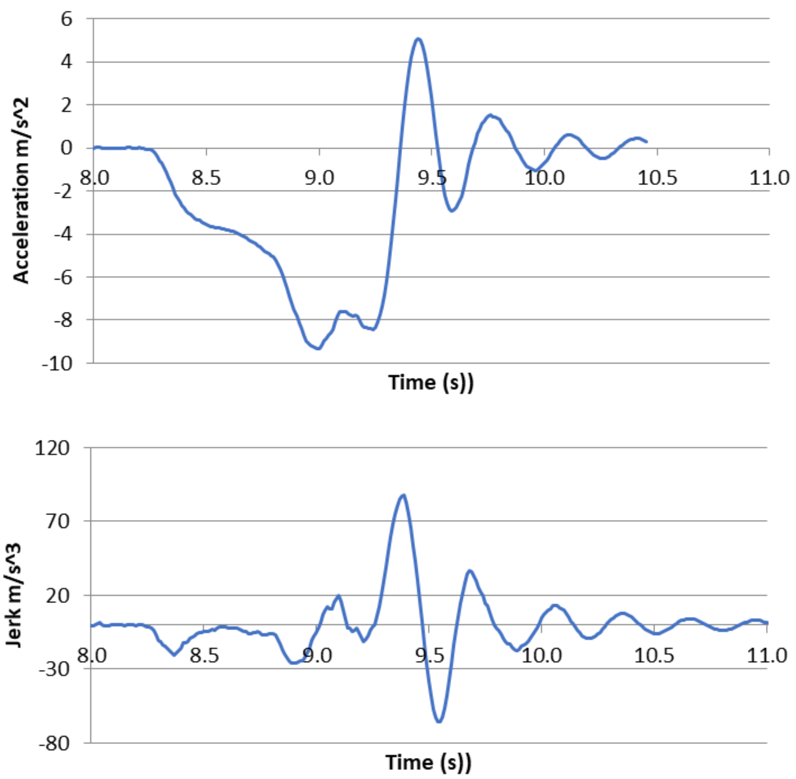


Figure 5: Longitudinal bus acceleration (top) and rate of change of acceleration (bottom): Moderate - avoided 75% pedestrian collisions

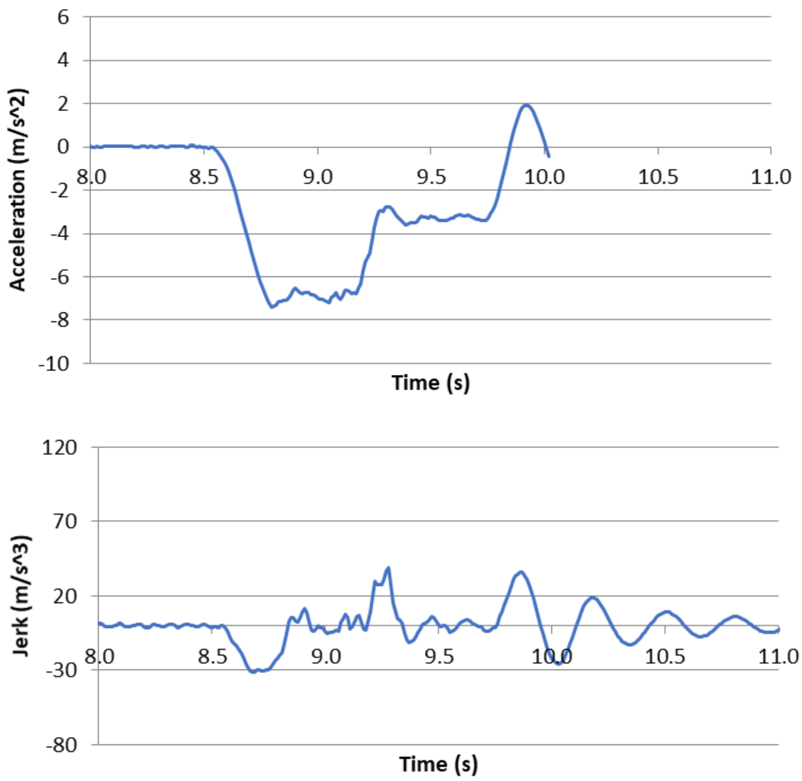


Figure 6: Longitudinal bus acceleration (top) and rate of change of acceleration (bottom): Difficult - failed to avoid 25% pedestrian collisions

It can be clearly seen that lower levels of deceleration were required to avoid collisions with a stationary car than was required for avoiding a crossing pedestrian, with peak decelerations of around 4 m/s^2 versus between around 7 to 9 m/s^2.

Different approaches can also be seen in different pedestrian tests. In the nominally less challenging situation, acceleration is initially increased to a modest level, then held for a while at that level before being increased to maximum before the end of the stop. The propensity of a person to fall under acceleration has been shown (De Graaf & Van Weperen, 1997) to be related both to the absolute level of acceleration and the rate of change of acceleration, often referred to as the ‘jerk’. This strategy helps to manage the ‘jerk’ and in the initial phase this is limited to an initial peak of around 20 m/s^3, though it peaks again at nearer 30 m/s^3 a little more than half a second later as the acceleration is increased again. These values are both clearly a long way above the thresholds proposed by the research for people standing without support with their heels together and above levels of acceleration described as a comfortable limit for occupants holding a hand-rail. However, the engineers on board the bus during these tests also conclusively showed that it was possible for alert passengers that were holding on in a stable initial position to easily withstand the acceleration without falls.

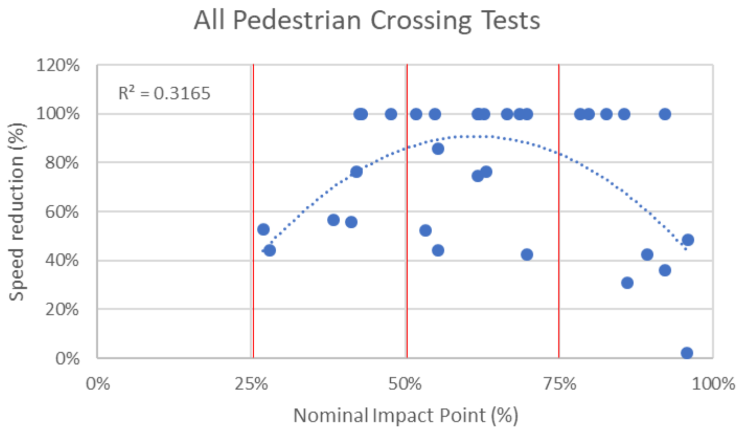
In the more difficult to avoid pedestrian test, the initial phase of modest deceleration was skipped, and the vehicle proceeded directly to a high level of acceleration >7 m/s^2. This did create a higher initial peak jerk of around 30 m/s^3. However, it should be noted that in all cases, the highest peaks in jerk occurred as the bus came to a stop, rather than as the brakes were initially applied.

In the pedestrian test, it could also be seen that the acceleration level reduced substantially part way through the stop. In this individual test, the impact speed was reduced but the impact was not avoided altogether. The reduction in acceleration occurred shortly after impact. The exact reason for this cannot be inferred from the test data but is not desirable from the point of view of avoiding running the pedestrian over after impact, because the pedestrian at this stage will be sliding/rolling along the road and must be decelerating at a lower rate than the bus to avoid runover.

5.2.3 Performance consistency

During testing it was noted that the results achieved were more inconsistent than expected. For example, in one configuration a heavy impact might be experienced in one test and avoidance in the next. The reason was not identified during testing. Both the AEB system itself and the test equipment required to evaluate it are very complex and problems are possible in both areas. In-depth analysis of the results and review of the video evidence in each case has shown that the main problem causing this variability was that the test equipment was not being as consistent as it should have been in placing the VRU dummy at the correct impact point. The test house that was responsible for running the test and operating the test equipment during this project have since investigated the causes of the inconsistency and have put several processes in place to prevent future occurrences and improve the robustness of test procedures.

The nominal impact point is the position at which the VRU dummy would have been expected to collide with the bus if no braking had taken place. It is expressed as the percentage of the width of the vehicle that the VRU crossed in front of before impact. The results can be seen in Figure 7, below.



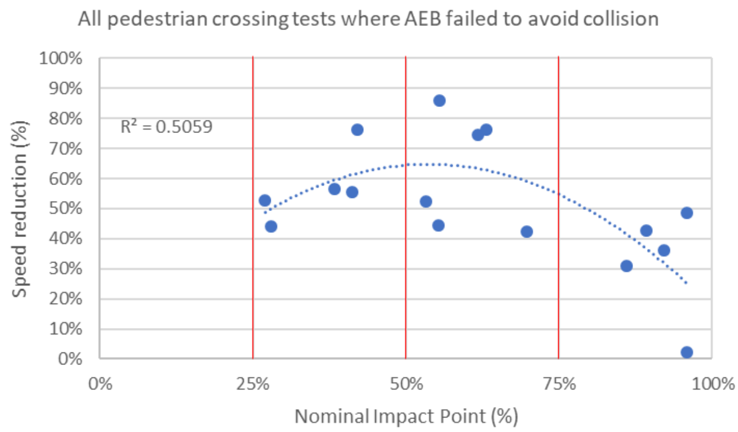


Figure 7: Effectiveness of AEB in relation to the nominal impact point

The first point to note is that the test protocol allows for tests at nominal impact positions of 25%, 50% and 75%. Each dot represents a single test and, therefore, they should have been arranged in vertical lines at each of these defined locations with only minimal scatter around those vertical lines. It can, therefore, be seen that the accuracy of the tests was substantially amiss.

It is important to highlight that only one input variable (nominal impact point) is plotted against the outcome in terms of speed reduction (the percent of the initial test speed that had been lost by the time of impact, or when bus came to rest). Several other input variables would be expected to influence the outcome: Bus speed, VRU speed, presence or not of masking vehicle, and direction of VRU movement (i.e. from nearside or farside).

However, the curved lines shown in the graphs are the best fit line based on a second order polynomial fit. The correlation factor (R^2) shows that almost one-third of the variability seen can be associated with the nominal impact point. This increases to half of the variability in results when only those that failed to avoid are considered. This suggests that the location of the impact on the front of the vehicle has a very strong influence on the effectiveness of the system.

There are explanations for this dependency on impact point. Firstly, it is difficult to accurately predict the path of pedestrians even when they are tracked accurately for some time. This is because they can accelerate, decelerate or change direction very quickly and without warning. Therefore, a pedestrian can be on a collision course with a bus for a significant time but the AEB will not apply braking until the pedestrian gets very close to entering the path of the vehicle. If the system intervenes earlier, with all other variables being equal, then it will increase the false positive rate. Based on this logic alone, it would be expected that performance would improve as the nominal impact point moves to the right (towards 100%). However, the same uncertainties and the need to avoid false positives also affects impacts at the extreme farside of the vehicle. When the nominal impact point is at 90%, for example, the pedestrian can easily avoid collision by accelerating. Thus, at a given time to collision, the system is less confident that a collision will occur than if the nominal impact point was more central. Thus, braking will be delayed until the level of certainty increases.

When the curved trend lines are considered then it does appear as if the fall-off in performance is greater when the nominal impact is at the farside of the vehicle compared with the nearside. However, it should be noted that the issue(s) causing the problem with nominal impact has not resulted in an even distribution. The lowest nominal impact point tested was 27%, with the pedestrian travelling more than a quarter of the distance across the bus before impact, whereas the highest was 96% such that it would have occurred at the very farside corner. It is likely that the drop-off each side would appear more balanced if more tests had occurred at the extreme nearside.

Other factors that were investigated included:

- **Low sun:** Low sun was present in some tests and not others. However, it did not appear to have a systematic observable effect on the results overall. That is, it is not the case that all test results where this was the case achieved lesser performance than those where it was not the case. This does not necessarily mean that it may not have affected a small number of individual results.
- **Steering:** Commercial vehicles tend to require more steering input than passenger cars and the steering robot was observed to have to apply significant steering to maintain the bus on the straight path. However, the analysis showed that both the rate of steering angle application and lateral path deviation remained within limits specified for cars in the Euro NCAP protocol.
- **Night-time performance**: The Euro NCAP protocol for testing passenger cars requires a certain level of street lighting. That is, it does not expect systems to be able to work in complete darkness or in areas with very poor street lighting. In the initial series of tests, the proving ground used did not have a Euro NCAP compliant lighting system available and it was apparent

that the ambient lighting present was much less bright than Euro NCAP require. Consequently, the camera was failing to recognise and categorise the pedestrian. Each of these tests was aborted. In one test, it was run to completion to see if radar recognition was sufficient to enable performance. In this single test, the VRU was successfully avoided based on radar recognition only. However, it was not known if this would be consistent and to avoid risk of equipment damage no further testing was undertaken.

Considering the inconsistent results described above, further testing of the true positive performance was undertaken at a different test location using different test equipment. Only a small subset of the original test program was evaluated and, whilst the tests still used a motion control platform to automate the movement of the VRU dummy, the speed and direction of the bus was controlled manually by a human driver instead of a robot driving system.

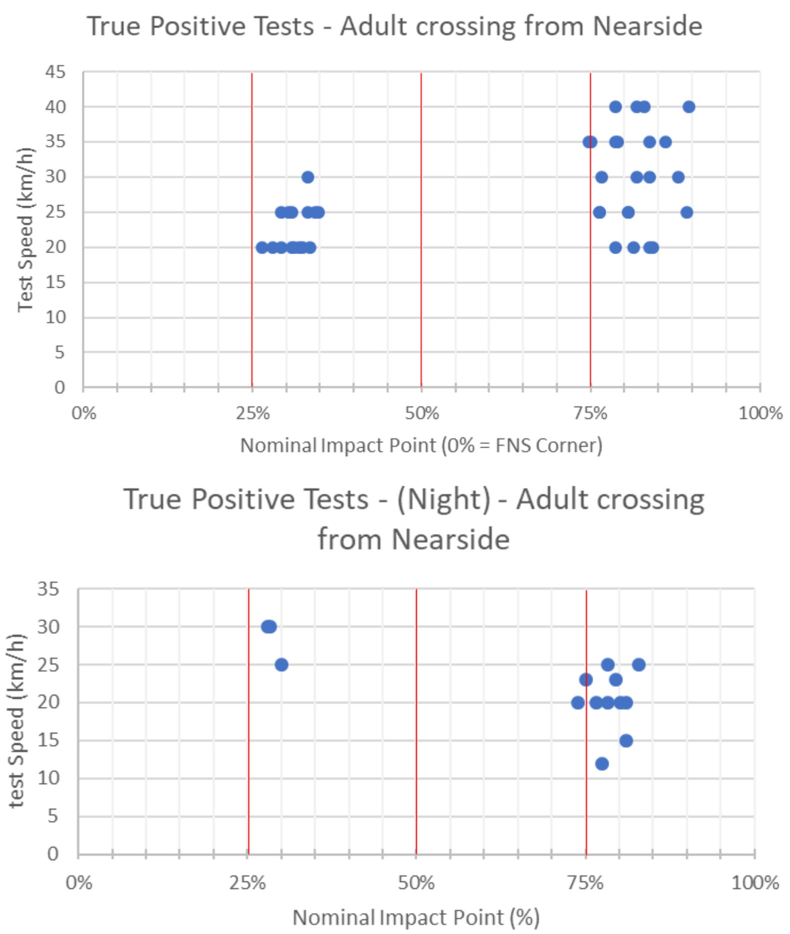


Figure 8: Distribution of nominal impact point

Figure 8 shows that the consistency of the nominal impact point was greatly improved during the second test program. The impact points were generally slightly higher (i.e. further across the front of the vehicle) than the target positions of 25%

and 75% but the grouping was more consistent. The results still contained more scatter than would be permitted in an official NCAP test. This supports the position that the test vehicle would need to be controlled by a robot driver during the official tests.

5.2.4 Performance summary

The tests of AEB showed that it offered substantial potential benefits in terms of avoiding collisions with pedestrians crossing in front of a bus, and cyclists and cars travelling in the same direction as the bus. The magnitude of speed reductions in pedestrian collisions was strongly dependent on the location of the impact on the front of the bus – the system is most effective for impacts in the central region of the front of the bus (25%-75%) and declined substantially as the impact point moved to the extreme edges of the vehicle.

The extent of braking applied was anything up to maximum Antilock Braking System (ABS) controlled braking. However, this was only applied as necessary to avoid the collision. In less urgent circumstances the braking was limited to around 4 m/s^2 and, wherever possible, braking was staged to provide a gentler ramp up to maximum.

6 Testing false positive performance

6.1 Rationale for tests

Table 5 showed that few of the available test procedures currently consider false positive activations with only the EU regulation on AEB and the US NCAP assessment actually including a false positive test.

The EU regulation specifies a False Reaction test whereby the test vehicle is driven between two stationary test vehicles that are separated by a distance of 4.5m. In this test the AEB must not provide a collision warning and must not initiate the emergency braking phase.

The US authorities (NHTSA, 2015) reviewed eight different potential false positive scenarios and acknowledged that no single test could ensure good false positive performance in the real world. They considered:

- A decelerating vehicle in an adjacent lane – straight road
- A decelerating vehicle in an adjacent lane – curved road
- Driving under an overhead bridge
- Driving over Botts Dots[3] in the roadway
- Driving over a steel trench plate
- A stationary vehicle at a curve entrance
- A stationary vehicle at a curve exit
- A Stationary roadside vehicle

Whilst several manoeuvres caused activations of the collision warning, only driving over the steel trench plate caused one of their test vehicles to apply automated braking. This was also the easiest test to set up and perform. Thus, this was the test selected for US NCAP.

Despite having the most comprehensive set of tests for true positive performance, Euro NCAP do not have any tests for false activation. It is understood that this is based on their position as an organisation aiming only to provide consumer information with the intention of promoting safety. The view was that true positive situations occur only very rarely, so most drivers do not experience them. Thus, consumer information is needed to inform drivers of how well their car will perform in those rare situations. However, if false positives become frequent, then it is warnings that will be most frequent, and the driver will quickly become aware of them. Drivers do not like excessive warnings and in a competitive market will turn away from those

[3] Note: Botts Dots are a form of road marking most commonly found in North America, they are a small round disc made typically of ceramic material used as a tactile lane marker analogous to rumble strips in the UK.

systems. This means that the market should be self-governing and that there is no need for them to correct a market failure by providing independent information.

There is little evidence to date of a significant problem with false positive brake applications in the passenger car market, so this does appear to be a valid view. However, buses represent a different challenge because a false positive activation risks injury to multiple passengers, both those that are standing and those that are seated-but-unrestrained. In the long term, it is expected that liability claims against manufacturers would in this case act as a strong market deterrent to excessive false positives. However, in order to require the system before such a track record has been established may require additional confidence in the false positive rate. Development of suitable false positive tests in a controlled environment is one way that this can be achieved.

Developers of systems have to drive at least hundreds of thousands, and possibly millions of kilometres with a particular system in order to be confident that the systems have reacted correctly in enough different traffic situations to be confident that their false positive rate will be very low. The algorithms used will also need to be tuned for each new application they are used in, possibly by re-running the scenarios measured in earlier road trials through the new set up in a simulated virtual environment. The prototype system evaluated as part of this project was not designed from scratch for a bus, it was adapted from a system used in other vehicle types. Thus, it had been through extensive development, but at the time of testing, had not been through the final 'tuning' process to adapt the algorithms specifically to use on a London bus.

Based on this, the reported view in (NHTSA, 2015) is likely to be correct. No single test can guarantee good false positive performance. Indeed, guaranteeing it would likely require thousands of different tests. However, it was considered that undertaking a road trial of a system that had not yet undergone final tuning for elimination of false positives would be likely to yield activations even in a short period in London traffic. Developing a short series of false positive tests based on these activations would, therefore, help to identify and catch-out under-developed systems before entering the market and act as a disincentive to any supplier not fully appreciating the quality levels required. However, even if successful, it must be emphasised that passing such tests will not guarantee a sufficiently low false positive rate in isolation. Responsibility for achieving this will still lie almost exclusively with the manufacturers.

6.2 Road trial – false positives

The road trial used a prototype AEB system which had not yet undergone tuning to remove false positives to a level that would be expected for a production-level system. Thus, at this stage, **false positives were fully expected** even in a short evaluation period and the **rate (per bus km) observed should not be considered representative of what the final production system will achieve**.

Although the main objective of the work was to characterise any false activations that occurred to help design a track-based false positive test, a secondary aim was to collect information that characterised normal manual driving and the frequency and severity of typical brake activations. This was essential information for quantifying the risk from brake applications as discussed in section 9. Information was also recorded in relation to normal throttle pedal activation to inform analyses of possible solutions to pedal confusion problems.

6.2.1 Test equipment

A single decker bus of similar type and construction to that which is typically used in London was used for the road trial. The vehicle was equipped with a prototype AEB system. The system was set up to operate in an open-loop or “Shadow Mode” – whereby it was effectively disconnected from the bus. It was actively monitoring the road environment, processing data and making decisions on warning and brake action, but the output signals were not connected to the bus and would activate only a special warning buzzer as part of the test equipment and connect to a data logger. Thus, the control of the vehicle remained fully with the driver and there was no chance of an unintended brake application being caused by the system.

A Racelogic Video VBox was used to record the following parameters:

- Speed and distance travelled
- GPS location
- Longitudinal and lateral acceleration
- Steering wheel angle
- Throttle and brake pedal position
- AEB Warning signal to bus
- AEB brake activation signal to bus
- Level of AEB brake demand to bus

As well as being recorded to a data file, the data was also overlaid onto a video (Figure 9) that was synchronised to four cameras that were positioned to provide:

- a forward-facing view through the front windscreen
- a side-facing view of the doorway and front windscreen
- a view of the driver’s reactions

Proprietary data was also recorded by the AEB supplier to facilitate post-processing and the identification of specific object(s) that caused any AEB activations.

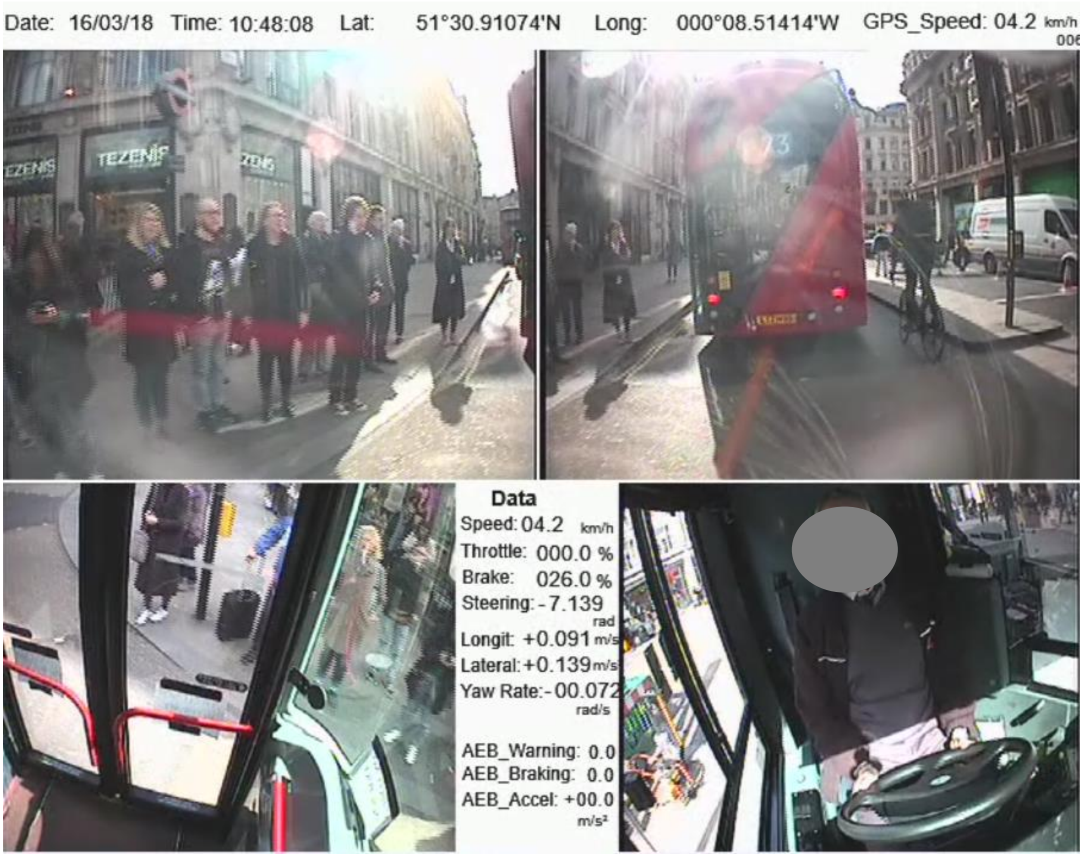


Figure 9: Video and data recorded during AEB road trial

6.2.2 Test procedure

The test vehicle was driven along five different bus routes in London over the course of five days, one day per route. The aim of the trial was to drive the vehicle in as normal a manner as if the bus was in service. To support this, the bus operators that run the chosen routes kindly provided experienced drivers who were familiar with the routes. Drivers were instructed to drive in their usual manner.

Each route was driven multiple times in each direction with as many journeys completed within the permitted driver’s hours.

6.2.3 Test routes

The routes selected included the wide range of bus driving environments likely to be encountered in service in London, whilst still being broadly representative of the most common routes and situations. Pedestrian collisions are the most frequent fatal collision type of relevance and situations with crowds of pedestrians are cited as difficult situations for AEB. Routes with a higher risk of such incidents were therefore included. Also, consideration was given to the occurrence of bus occupant injuries in incidents without a collision, since these represent a potential disbenefit to AEB if the system delivers high levels of deceleration. To ensure that the overall test program was representative of the varied routes experienced in London, a route considered to have a lower risk of pedestrian casualties was also selected.

A full detail of the analysis to support the route selection is provided in Appendix A.

The selected routes for the road trial were:

- #75: Lewisham Station to Fairfield Halls
- #55: Lea Bridge Road/Bakers Arms to Oxford Circus
- #149: Edmonton Green Bus Station to London Bridge Station
- #174: Dagnam Park Square to CEME
- #159: Streatham Station to Marble Arch Station

Figure 10 shows each route on a map.

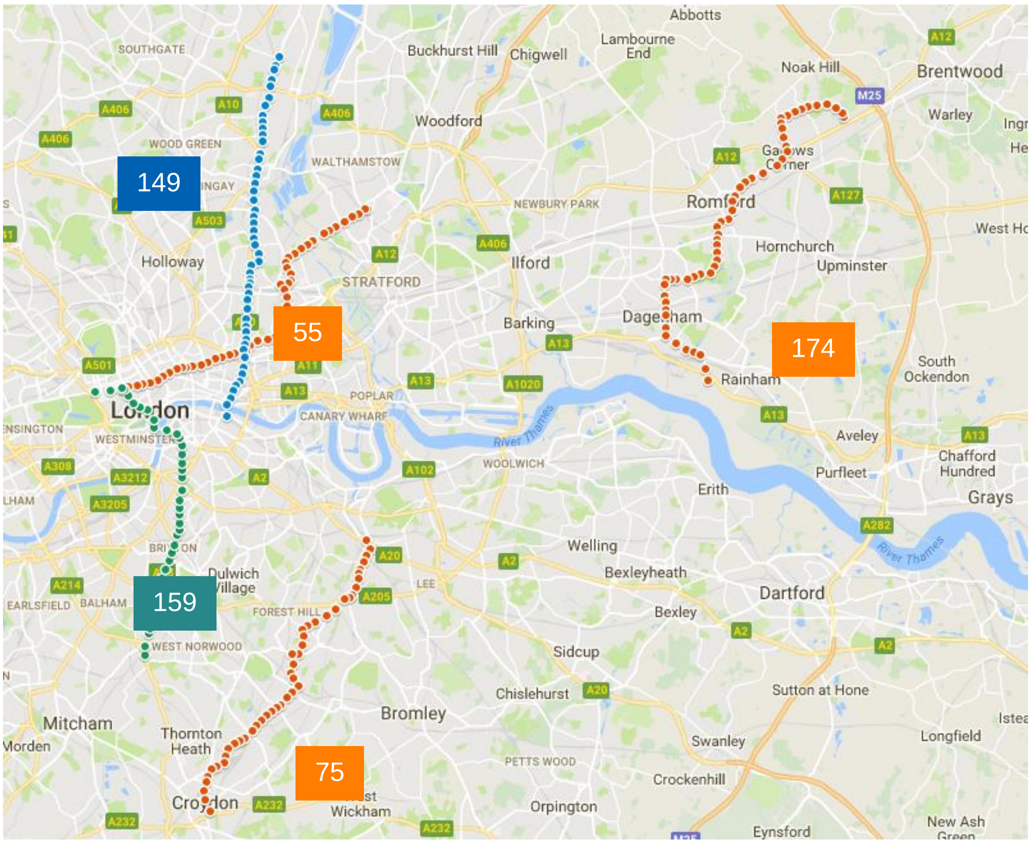


Figure 10: Test routes for AEB road trial

6.2.4 Road trial results

Six different drivers drove the vehicle a total of 399km during the week, covering the five different routes listed above with an average speed of 12.9 km/h. During this time there were a total of 3,032 braking events (all initiated by the driver), an average of 7.6 events per km.

Figure 11 shows that there were no brake applications that resulted in a peak deceleration greater than 3.5m/s², with 96.7% of events having a peak deceleration of less than 2m/s².

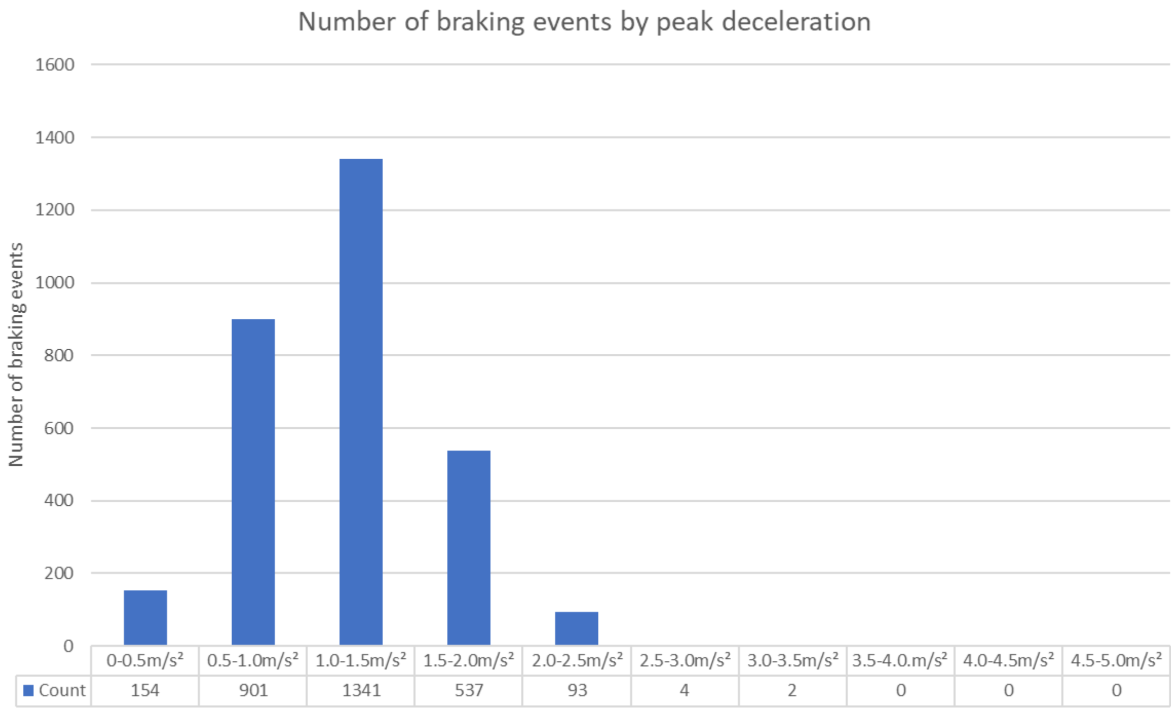


Figure 11: Number of braking events during AEB road trial by peak deceleration

In total, 17 system activations were logged during the road trial where braking would have occurred if the system was fully operational. In seven cases, the system demand would have been limited to a deceleration 4m/s² and in the remaining ten cases it would have peaked at a demand of between 8.0m/s² – 9.8m/s²).

What the brake system would actually have *delivered* in response to these braking demands depends on the duration for which they were demanded and the initial speed because air brake systems are relatively slow to react and build up compared with hydraulic systems. To estimate this lag, information from the vehicle manufacturer and data from the true positive test programme was used. Firstly, the tier one supplier indicated that it would take approximately 0.15 seconds for the AEB signal to be delivered to the braking system. In addition, the results from the true positive tests then showed that it would take a further 0.05 seconds before the deceleration began to ramp up (Figure 12).

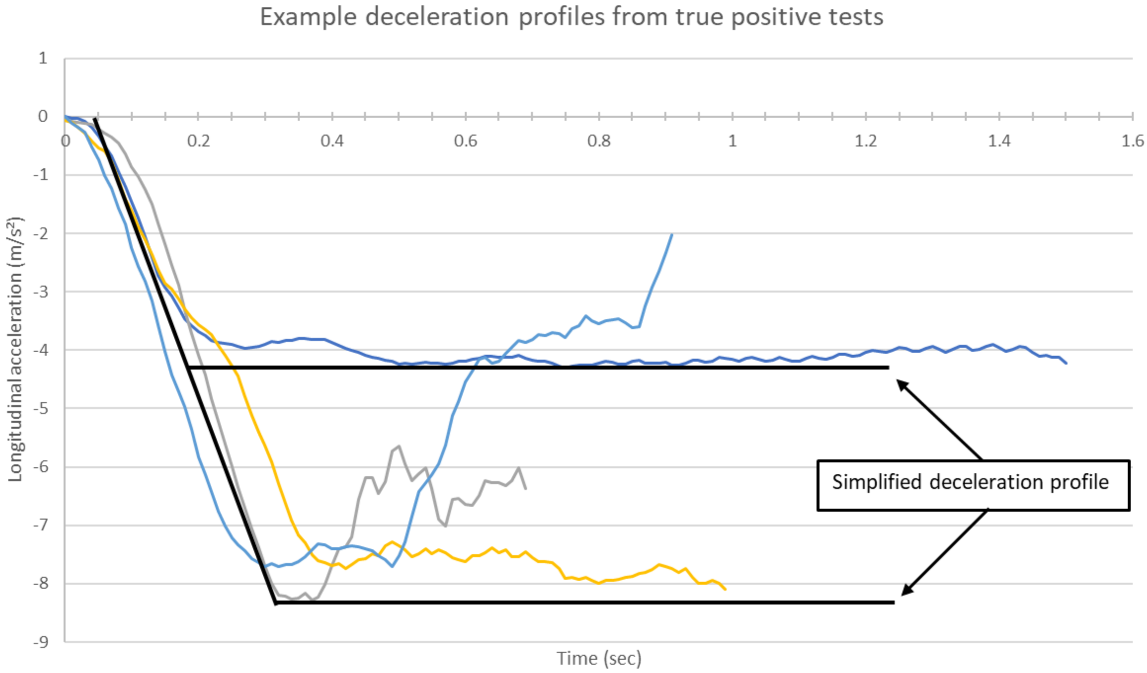


Figure 12: Example deceleration profiles from true positive test

Based on this information, a simplified deceleration profile of the actual level of braking that occurred during each false positive event was calculated, as illustrated by the example in Figure 12.

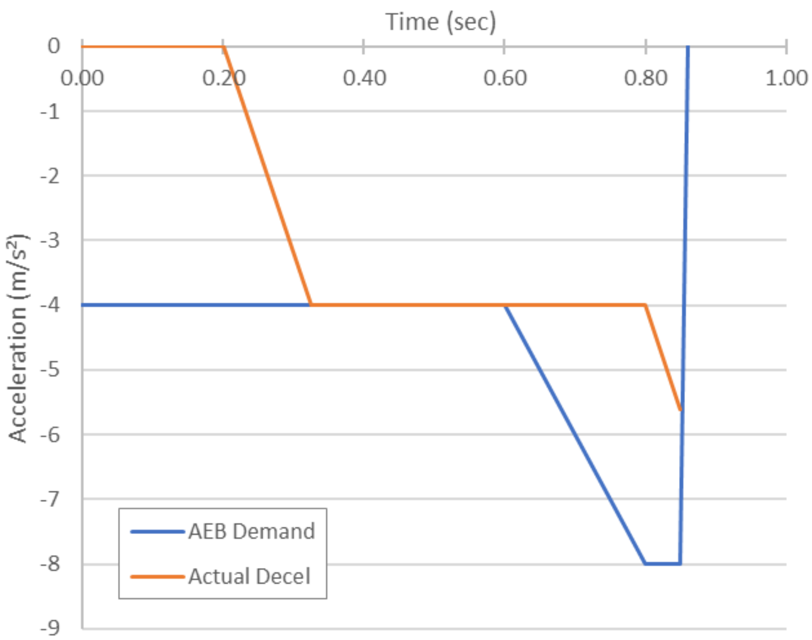


Figure 13: Comparison of braking demand and actual estimated braking

By applying the estimated response of the braking system to the level of deceleration demands by the system it could be seen that, in some cases, the actual peak deceleration of the bus was lower than the peak demand (Figure 13). In four of the 17 false positive events (24%) the duration of the demand would have been too short for there to be any deceleration at all, as in Figure 14.

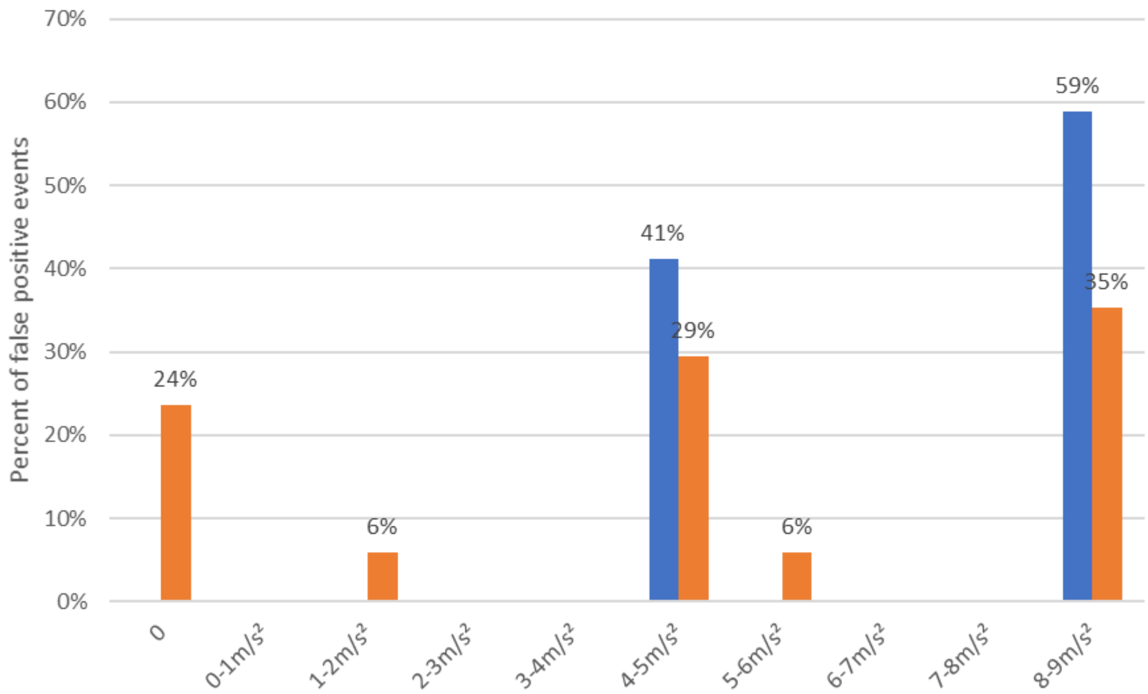


Figure 14: Comparison of AEB demand and actual deceleration for false positive events (road trial)

The false positive events that produced the greatest peak deceleration were all cases in which the level of deceleration ramped up over the duration of the event. Feedback from the tier-1 supplier indicated that this was a result of running the AEB system in an “open-loop” mode such that no actual braking took place. For example, Figure 15 shows one event where the AEB system initially demanded a deceleration of 4m/s². Since the system detected that no actual braking had occurred, and in that time the vehicle was now closer to the object in front, it decided that it would now require a higher level of deceleration in order to avoid a collision and therefore the deceleration was increased up to a maximum.

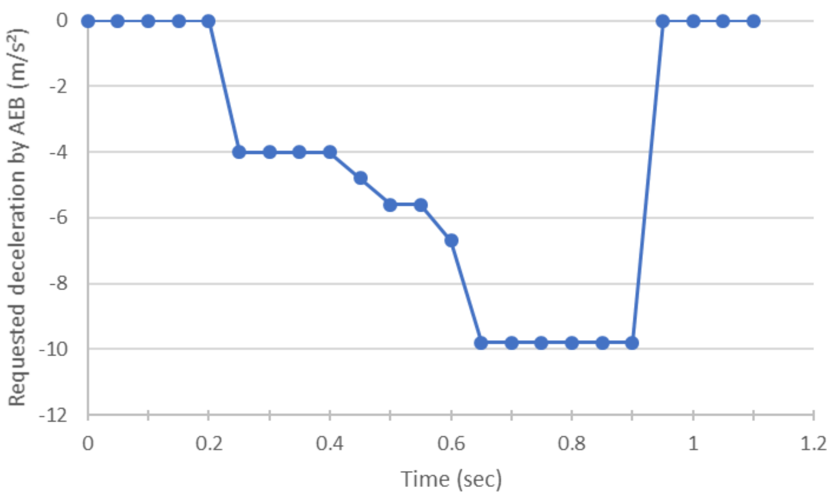


Figure 15: Example of increasing AEB brake demand during open-loop operation

The peak value of deceleration that would have been requested during normal "closed-loop" operation is unknown, but it is reasonable to expect that it would be somewhere between the initial requested deceleration of $4m/s^2$ and the peak deceleration of $7.5m/s^2$ observed during the tracks tests undertaken as part of the protocol development.

In terms of categorising types of false positive, four main groups were identified based on reviewing the TRL video of the scene:

1. There was no obvious cause of the activation, an obvious false positive.
2. There was at least one pedestrian moving on a potential collision course but then stopping, changing direction or moving back. Possibly false activation, possibly simply premature and possibly considered true positive if, despite an apparent low collision risk, the driver also manually braked in response to the same events.
3. There was steering around corners or in towards the kerb (e.g. bus stops) and there were pedestrians or fixed objects on the kerb that at least momentarily appeared to be on a collision course, likely to be a false positive depending on exact timings involved.
4. Moving off from rest at the same time as vehicles ahead (cyclists in two cases, bus in one), the equipped vehicle was momentarily gaining on the vehicles ahead. These were more a premature intervention than an entirely false one.

The latter three groups are all situations similar to those that were identified in earlier research (e.g. (Seiniger, et al., 2014)) and in good production systems have largely been tuned out (at least for brake interventions if not always warnings). The tier one supplier was confident these could be tuned out of a production-level system without substantial effects on true positive performance. These situations are also amenable to the development of track-based tests to try to identify systems that have not been properly tuned.

6.3 Track tests – false positive

From the four scenarios identified in the road trial the following two were selected for the subsequent track test programme:

- Aborted pedestrian crossing
- Bus stop manoeuvre

6.3.1 Test scenarios

For the aborted crossing scenario (Figure 16), the test was configured so that the VRU dummy walked to cross in front of the bus from the nearside but stopped quickly before entering the path of the bus. The movements of the bus and VRU dummy were timed to give a nominal impact point of 25% had the speeds remained constant. The speed of the bus varied between 20km/h and 40km/h and the VRU dummy was programmed to stop at lateral distances between 0.6m and 0.9m away from the front-nearside corner of the bus.

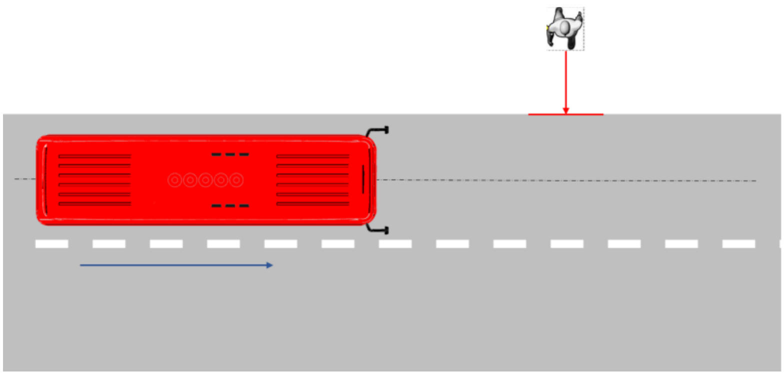


Figure 16: Test configuration for aborted crossing scenario

For the bus stop manoeuvre (Figure 17), the bus followed a path with a radius of 125m such that it was travelling straight ahead again at the time it passed a stationary VRU dummy that was positioned to the nearside of the bus. The speed of the bus varied between 20km/h and 30km/h and the lateral position of VRU dummy outside the front-nearside corner of the bus was between 0.23m and 0.83m.

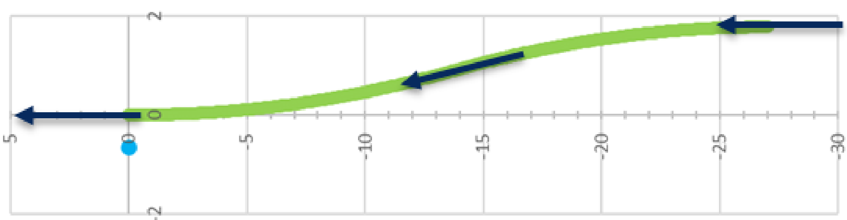


Figure 17: Test configuration for bus stop test

6.3.2 Test results

Figure 18 shows the results from the aborted crossing tests. It shows relationship between then nominal impact speed of VRU dummy on the bus, the lateral distance at which the VRU dummy stopped moving, and whether the test resulted in an AEB activation.

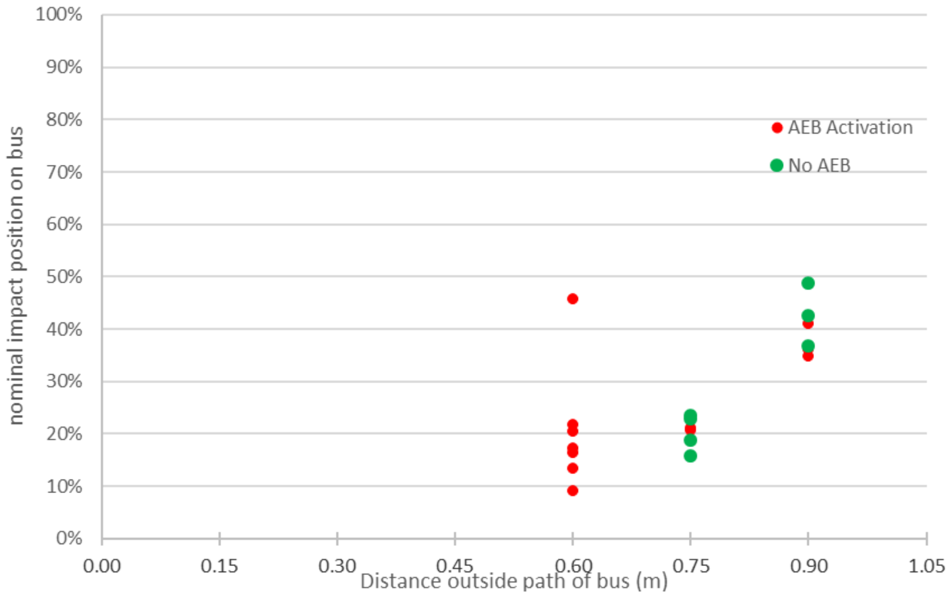


Figure 18: Aborted pedestrian crossing test - nominal impact speed of VRU dummy on the bus compared to the lateral stopping point of the VRU dummy

In the test configuration where the VRU dummy stopped closest to the passing bus (0.6m lateral distance), the AEB activated in all the tests. For the scenarios where the VRU dummy stopped further away from the bus (0.75m and 0.9m lateral distance) most of the tests resulted in no AEB activation.

For the bus stop test, Figure 19 shows the position along the bus path at which point the AEB system activated or provided an audible warning. The red section of the path is the point at which the instantaneous direction of the bus was aligned with the VRU dummy and would therefore have collided with the VRU dummy had no further steering been applied from that point. Clearly, as the VRU dummy is positioned such that it has a greater lateral distance to the path of the vehicle then then proportion of the bus path where the bus is aligned with the VRU dummy is reduced.

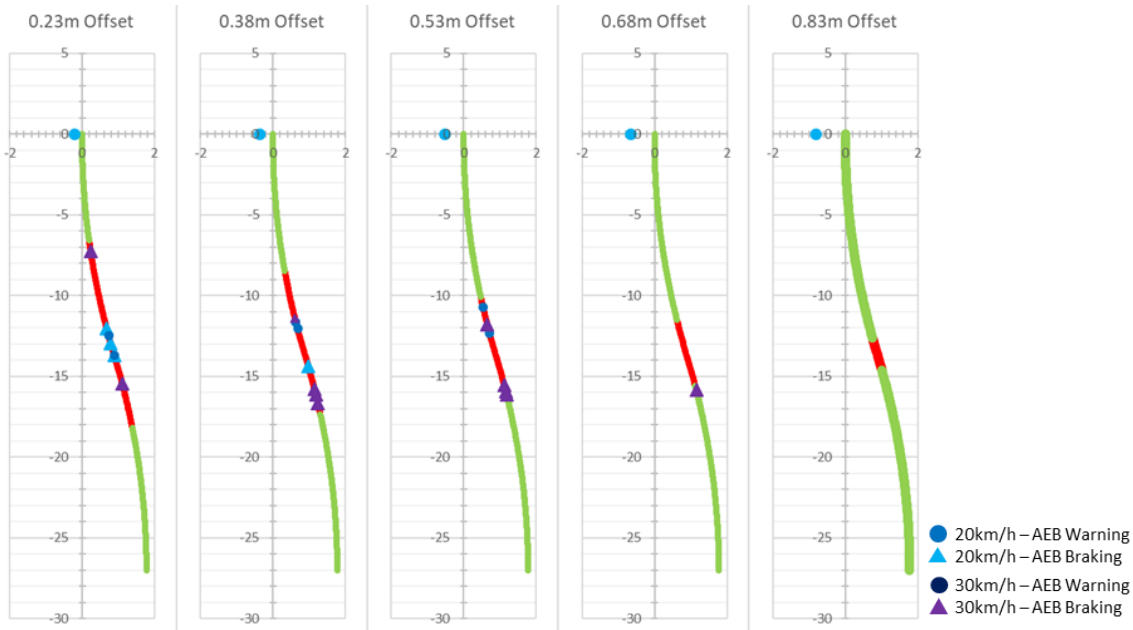


Figure 19: Bus stop test results

The results show that the smaller the lateral distance is between the VRU dummy and the passing bus, then the more likely it is for the AEB to activate. The pattern of results shows that the AEB typically activated the brakes at a longitudinal distance of between 12-17m away from the VRU dummy. The timing of these activations is somewhat surprising because they occur well before the point-of-last-brake or point-of-last steer.

6.3.3 Summary

The track test programme highlighted considerable variability in the nominal impact position. This was at least partly caused by inconsistency with the test equipment and has highlighted the importance of tightly controlling the test parameters within official tests. Despite this it was possible to pick selected results that were close to the conditions specified by the protocol. In these cases, the performance of the AEB generally matched that expected by the manufacturers of the system.

A road trial of approximately 400 km did identify a significant number of activations of the prototype system and these require additional analyses. It is expected that these instances would be tuned out before production such that the rate per km is not realistic at this time. The trial also allowed quantification of 'normal' human braking behaviour. Braking events were found to be high frequency but predominantly very low deceleration. There were thousands of events with a peak deceleration of less than 1.5 $m/s^2$and none with more than 3.5 m/s^2.

Relatively few testing or approval regimes require a false positive test because it is recognised that one or two individual tests cannot guarantee an adequately low false positive rate in service. However, it can be a disincentive to the introduction of immature systems. The tests selected addressed the scenarios most typically observed during the road trial and were able to highlight different levels of performance for different test configurations.

7 Protocol development

The aim of this project, wherever possible, is to base decisions on the inclusion of different test scenarios, and the weighting of the importance of each variable within the overall test score, on the risk to casualties.

7.1 Protocol weightings

7.1.1 Collision type

AEB can be effective in crash types involving different road user groups. Section 8 identifies potential target populations and effectiveness estimates for the main crash types that are within scope of TfL's specification and the abilities of the prototype AEB system evaluated.

The figures are shown in Table 6, which is based on the casualty data extracted from the STATS19 database for each casualty type involved in a collision with a bus in the relevant collision scenario. The weighting factor was added based on the proportion of monetised casualty benefit[4] that is attributed to each collision type.

Table 6: Protocol weighting for collision type based on annual average target populations.

Crash type	Average annual target population				Monetised benefit	Weighting
	Fatal	Serious	Slight	Total	(£million)	
Bus front to Pedestrian Crossing	4.2	35.7	101	140.9	£16.7m	94%
Bus front to Cyclist Rear	0	0.6	7	7.6	£0.2m	1%
Bus front to Car Rear	0	1.2	41.6	42.8	£0.9m	5%
Total	4.2	37.5	149.6	191.3	£17.9m	100%

Most of the benefit (94%) comes from collisions between buses and pedestrians. However, systems that can work in pedestrian crossing collisions will tend to work in the front-to-rear collisions as well and the additional burden of tests for cars and cyclists does not necessarily need to be high. It was, therefore considered that all three should remain in scope of the final test protocol and, in the assessment of test results, weightings of the results achieved in each area should be based on the proportions above. However, it is noted that where values are small, such as for the

[4] The UK Department for Transport publish monetary values that they use to assess the value of casualty prevention, divided by the severity of the casualty. The monetised prevention value referred to here is the number of fatal casualties multiplied by the DfT casualty prevention value for fatalities, plus the number of serious casualties multiplied by the serious value etc.

cyclist test above, it is reasonable to round figures up to ensure simplicity and that any included test has at least some significant value to the outcome.

As such 85%, 5% and 10% would be an acceptable alternative to the actual precise figures since this provided a minimum of 5% for the smallest casualty group and still provides some differentiation between cyclist and car occupant casualties.

In the passenger car market, AEB systems are now being marketed that are capable of mitigating collisions where the equipped vehicle turns across the path of an oncoming vehicle (e.g. turning right from main road into minor road across oncoming traffic) and where a vehicle crosses the path of the equipped vehicle (e.g. if a vehicle jumps red lights at a cross roads). The target population for these crash types can only be identified at a high level in STATS 19 (e.g. the front of the bus hits the side of a car when the bus is turning right or going ahead other and car going ahead other). The effectiveness of these systems within their target crash type is also not known. However, if a similar effectiveness is assumed to apply to all the identified target population then the potential benefit would be of a similar order of magnitude to the bus-front to car-rear collisions. However, the cross-traffic scenario may add significant sensor costs to enable a sufficiently wide field of view, the technology is not yet under development for buses and is likely to lag passenger cars by at least two years. In addition to this, the tests required to evaluate performance are more complex and requires more sophisticated equipment.

For these reasons, the additional functions have not been added to the protocol as developed at this stage. However, the functions have been added to the future roadmap for consideration if analysis suggests they can be included at a sufficiently low marginal additional cost (over and above the AEB considered now) to ensure cost-effectiveness.

7.1.2 Crossing or walking in the road

STATS19 data for London between 2005 and 2015 shows that there were 44 fatalities where the front of a bus collided with a pedestrian whilst undertaking a relevant manoeuvre (e.g. not turning left or right etc). Forty-three of those fatalities involved a pedestrian crossing the road and the remaining one involved a pedestrian that was stationary in the road (standing or playing). None were walking along the road and even when all severities were considered only 18 of 1483 (1.2%) of pedestrians were walking along the road (0 fatal, two serious, and 16 slight injuries in 11 years). Thus, no further consideration has been given to tests of AEB in longitudinal collisions with pedestrians and all focus was placed on crossing collisions.

7.1.3 Pedestrian and vehicle speed

No evidence was identified on the actual speed of pedestrians involved in real London collisions. It was, therefore considered that the speeds tested would be the same as for Euro NCAP (3km/h, 5km/h and 8km/h) and no weighting should be applied based on pedestrian speed.

Information on the speed of the vehicle when it collided with a pedestrian was available from two sources: the study of police fatal collision reports undertaken by

(Edwards, et al., 2017) and the analysis of CCTV records of collisions experienced by a London operator. The data in (Edwards, et al., 2017) all involved fatalities and the CCTV records all related to non-fatal pedestrian casualties. The cumulative frequency of different travel speeds (prior to any braking) is shown in Figure 20, below.

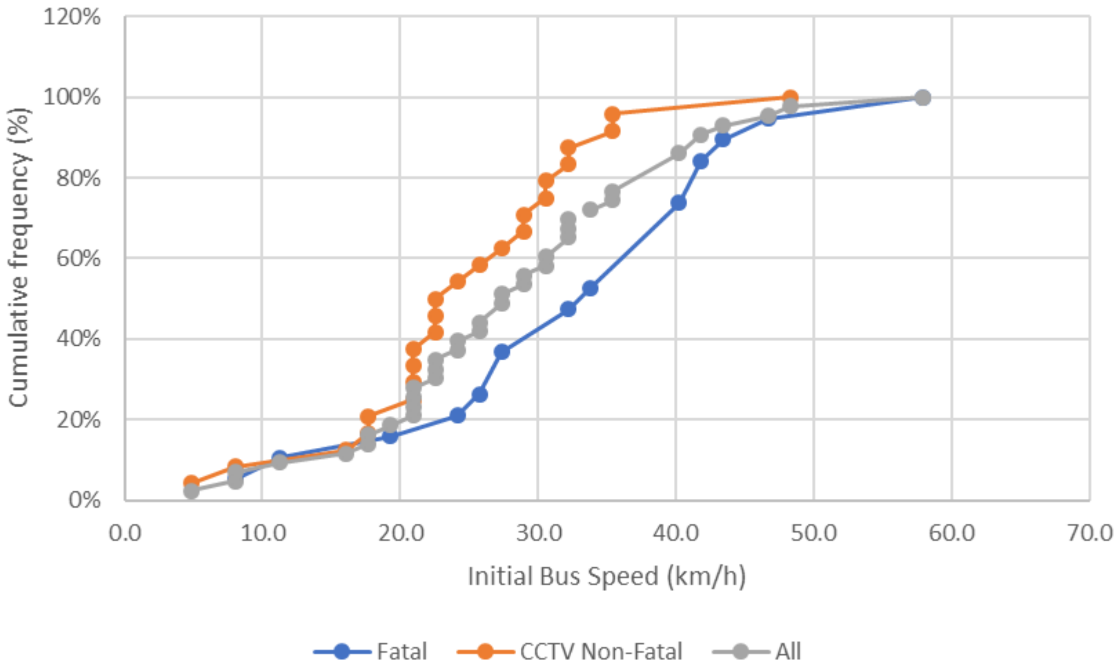


Figure 20: Cumulative frequency of pedestrian collisions by initial bus speed

Figure 20 shows that the recorded impacts all had initial speeds of less than 60km/h (37mile/h) so there would have been no benefit to having a system that worked from a higher initial speed than this. However, the true positive performance of pedestrian AEB on buses is limited by the need to avoid false positives, the reaction and build up time of the air brake systems and the maximum deceleration that the brakes can achieve. There is no benefit to testing and giving incentive for performance levels that cannot be achieved, or that would require prohibitively expensive technical solutions. Thus, the demands of the test become a balance between the need for solutions as defined by collision data and the technical feasibility of the solution. The overall aim is to encourage market penetration of the best performing systems currently available whilst allowing headroom for solutions that could be brought to market in the short term. The long-term development of better solutions is incentivised through commitments in the future roadmap to upgrade requirements (where the collision data identifies a need) when the technology is becoming available.

Based on the performance achieved by the prototype system tested during this project, consideration of the performance levels of car systems (see www.Euro NCAP.com) and the fundamental additional limitations of bus braking, it was considered that a range of test speeds from 10 to 50 km/h was appropriate.

Tests of performance are undertaken every 5km/h in Euro NCAP and no evidence has been identified to suggest that this should change. The data on collision speed has therefore been divided into 5km/h groups from 10km/h to 50km/h to reflect the tests. This has been completed separately for each data source and then for the combined data, weighted by consideration of the casualty prevention value for fatal and non-fatal pedestrian collisions. The weighting factor was defined by calculating the non-fatal casualty prevention value based on the monetised value associated with the actual number of serious and slight pedestrian casualties from collisions with a bus in London. The results are shown below in Figure 21.

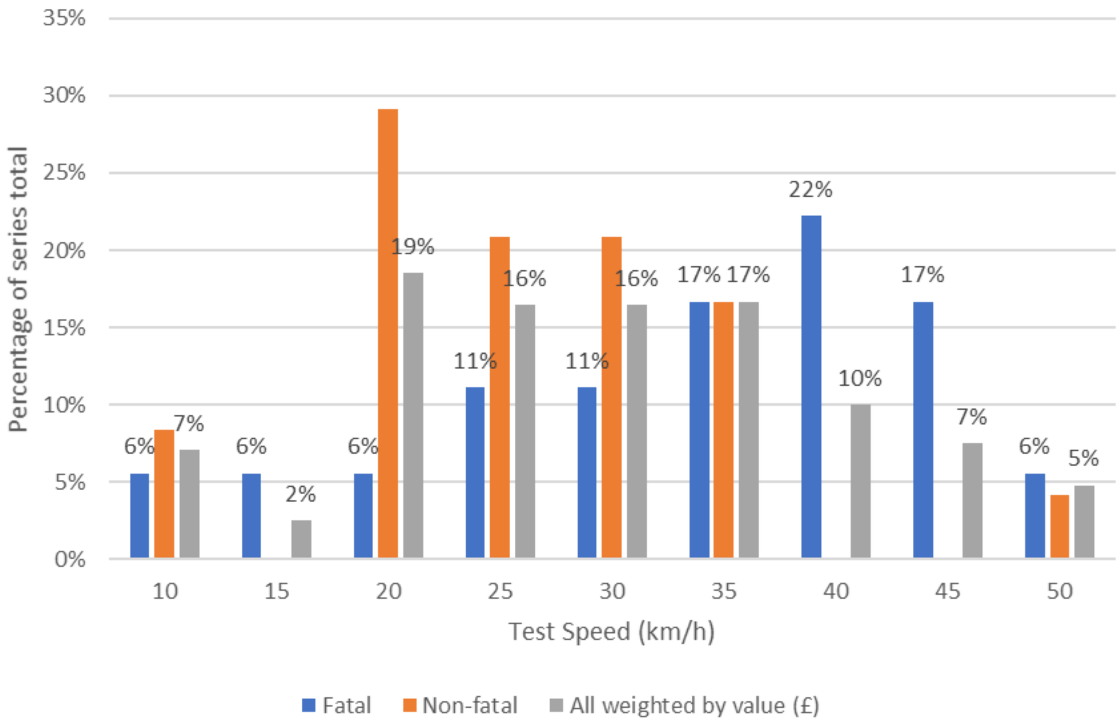


Figure 21: Distribution of casualty prevention value by casualty type and travel speed

7.1.4 Crossing direction and masking

Data from STATS 19 was grouped into categories reflecting the Euro NCAP test configurations for crossing direction and masking and was weighted by casualty severity based on the relative casualty prevention value, as in Table 7.

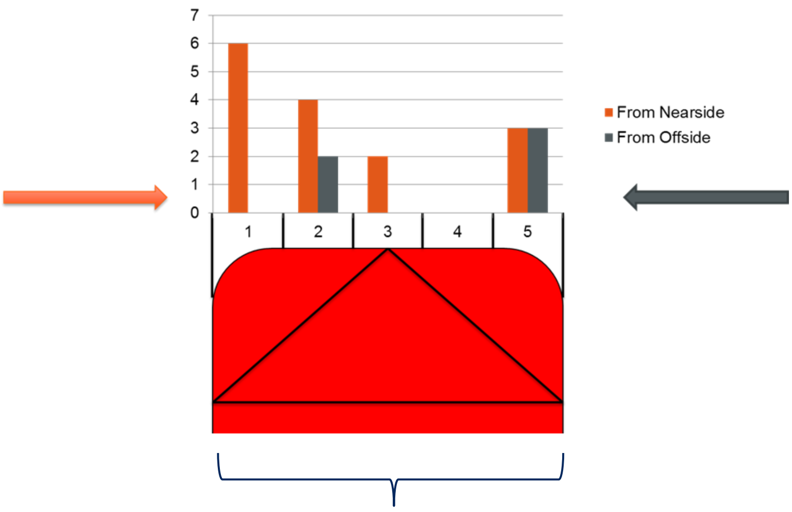
Table 7: Collision data to support weighting for crossing direction

	Manoeuvre	Fatal	Serious	Slight	Total	
Stats 19	Crossing from driver's nearside	28	265	710	1003	
	Crossing from nearside – masked	2	24	42	68	
	Crossing from driver's offside	13	60	222	295	
	Crossing from offside – masked	0	10	38	48	
		Casualty prevention value				**Weight**
Derived	Farside unobstructed	£23,937,095	£12,414,734	£3,541,086	£39,892,915	24%
	Nearside unobstructed	£51,556,819	£54,831,743	£11,325,096	£117,713,658	69%
	Masked by vehicles	£3,682,630	£7,035,016	£1,276,067	£11,993,713	7%
	Total (derived)	£79,176,543	£74,281,494	£16,142,249	£169,600,286	100%

Crossing from the nearside without obstruction has by some margin the highest casualty prevention value. Masking by parked vehicles is a relatively small contributor but is believed to frequently involve children and can, therefore, be emotive.

7.1.5 Impact point on bus

The only information available regarding the impact point was that available from the fatal study reported by (Edwards, et al., 2017). This divided the front of the vehicle into five equal zones and counted the number of fatalities where it was known contact occurred in each zone, as shown in Figure 22.



Nearside: 1 – 6 fatalities

2 – 6 fatalities

3 – 2 fatalities

4 – 0 fatalities

Farside: 5 – 6 fatalities

Figure 22: Distribution of impact point on bus. (Source: Edwards et al, 2018)

Euro NCAP uses only three impact points, 25%, 50% and 75%. Thus, the available data does not match perfectly and was rationalised to three categories by assuming the collisions in groups 2 and 4 above were split evenly between the adjacent categories. This result in the distribution shown in Table 8. The nearside third was assumed to be represented by the 25% impact point, central by the 50% and farside by the 75% impact point.

Table 8: Distribution of impact point on bus

Impact point	Casualties	Weight
Nearside third	9	45%
Central third	5	25%
Farside third	6	30%
Total	20	100%

7.1.6 Lighting conditions

The STATS19 data was divided by the recorded lighting conditions. Table 9 shows that casualties were split between those that occurred during daylight (63%) and those that occurred at night and with streetlights (37%).

Table 9: Collision data to support lighting conditions weighting

Lighting Condition	Fatal	Serious	Slight	Total	
Darkness - lighting unknown	0	0	2	2	
Darkness - lights lit	17	127	256	400	
Darkness - lights unlit	1	0	0	1	
Daylight	25	232	754	1011	
Total	43	359	1012	1414	
Monetised casualty benefit	**Fatal**	**Serious**	**Slight**	**Total**	**Weight**
Daylight	£46,032,874	£48,003,639	£12,026,932	£106,063,446	63%
Dark-streetlit	£31,302,354	£26,277,854	£4,083,415	£61,663,623	37%
Total of these two	£77,335,228	£74,281,494	£16,110,347	£167,727,069	100%

7.1.7 Analysis, selection and weighting of detailed variables

If all permutations of variables were to be enumerated in the collision data, the individual weightings would be affected by having small samples sizes such that repeating the analyses in different years would likely give different results. Thus, an analysis has been undertaken assuming each variable is independent (e.g. that whether the collision occurred in day or in darkness with streetlights would not affect the probability that it was a nearside, central or farside impact). This gives rise to the following matrix:

Table 10: Total bus casualty value by direction, impact point and lighting condition

Direction/obstruction	Weight	Impact point	Weight	Lighting		
				Day	Night	Total
Farside unobstructed	24%	25	45%	6.7%	3.9%	10.6%
	24%	50	25%	3.7%	2.2%	5.9%
	24%	75	30%	4.5%	2.6%	7.1%
Nearside unobstructed	69%	25	45%	19.8%	11.5%	31.2%
	69%	50	25%	11.0%	6.4%	17.4%
	69%	75	30%	13.2%	7.7%	20.8%
All masked	7%	25	45%	2.0%	1.2%	3.2%
	7%	50	25%	1.1%	0.6%	1.8%
	7%	75	30%	1.3%	0.8%	2.1%
			Total	**63.2%**	**36.8%**	**100.0%**

The Euro NCAP test configurations are highlighted in orange in Table 10. These configurations capture most of the most important groups and, in total, represents approximately 57% of the total bus casualty prevention value. It could be argued that it would be more representative to add a nearside unobstructed test at 50% impact point, but it is also very likely that if an AEB system performs well at 25% and 75% then it will also perform well at 50%, whereas the reverse does not necessarily hold true. On this logic, and based on a larger casualty group, it could be considered to swap from a 50% impact point in the farside test to a 25% one. However, in Euro NCAP tests, the VRU dummy is moving at its fastest in this test such that good performance at a 25% impact point may not be technically feasible in the short term. Overall, no evidence was considered sufficient to change from the basic crossing configurations defined for cars by Euro NCAP has been identified.

When considering weighting the importance of each configuration, the numbers above would lead to an artificially low score if 100% was the maximum, purely because not all conditions are tested. Therefore, the results were normalised against the maximum available for the 57% of the total bus casualty prevention value that is directly represented by the tests. This results in the distribution shown in Table 11. In the ratings the following approach was taken and the weightings applied accordingly:

- Farside scenario was considered to represent all farside collisions,
- Nearside scenarios were considered to represent all nearside collisions,
- Masked scenario was considered to represent all masked collisions,
- Nearside adult scenarios that weighting was divided by 25/75,
- Night and day in accordance with the proportions of the total casualties for that lighting condition.

Table 11: Normalised distribution of casualty prevention value for selected true positive tests

Test configuration	Day	Night	Total
Bus-to-Adult, Farside 50% (BPFA50)	7%		7%
Bus-to-Adult, Nearside 25% (BPNA25)	35%	20%	55%
Bus-to-Adult, Nearside 75% (BPNA75)	23%	13%	37%
Bus-to-Child, Nearside 50% (BPNC50)	2%		2%
Total	66%	34%	100%

7.1.8 False positive test scoring

Two configurations of the bus stop tests have been proposed for the protocol; one assessing the true positive performance and the other assessing the false positive performance. Initially it was only considered necessary to include a single false positive test for the bus stop scenario and that any activation of the AEB during that test would result in the AEB system being awarded a zero score. However, the peer review of this project highlighted that the bus stop test was the only test in which steering input was required and, to avoid the zero score, it might be possible for a system to be designed such that the AEB worked normally for the straight-line tests but was deactivated as soon as steering input was detected. To avoid this undesirable situation, a true positive bus stop test was therefore added to the test protocol with the requirement that the AEB must produce an activation in the true positive test to avoid being awarded a zero score. It should be noted that this true positive is untested at this stage so the exact effects and ability for the equipment to reproduce it have not been proven.

For the aborted crossing test, it was not possible to use collision statistics directly because the scenario does not exist in current collision data. Therefore, the scoring was based on the logic that for a system to achieve a good true positive braking performance it might be necessary for braking to occur when the VRU is outside the path of the bus. For the closest lateral distance at which the VRU dummy stops, AEB activation is permitted but maximum points are only awarded if the peak deceleration measured is less than $7 m/s^2$. For the cases where the VRU stops further away from the path of the bus, then maximum points are awarded if no activation occurs and one point is awarded if the peak deceleration measured is less than $7 m/s^2$.

7.2 Protocol test scenarios selected

Based on the above analysis, the following test scenarios have been selected for inclusion in the AEB test protocol.

7.2.1 Car tests

The performance of the AEB system will be assessed in relation to a stationary target only, and as shown in Figure 23.

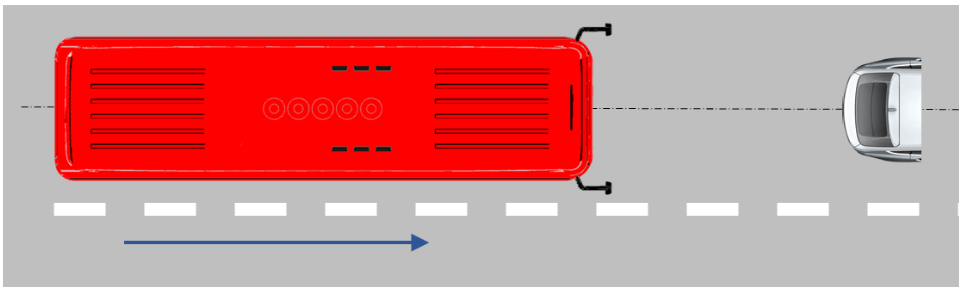


Figure 23: Car test scenario

7.2.2 *Pedestrian crossing tests*

The performance of the system will be assessed for the scenarios of an adult walking from the nearside, an adult running from the farside and for a child running from the nearside from behind obstructing vehicles, as shown in Figure 24.

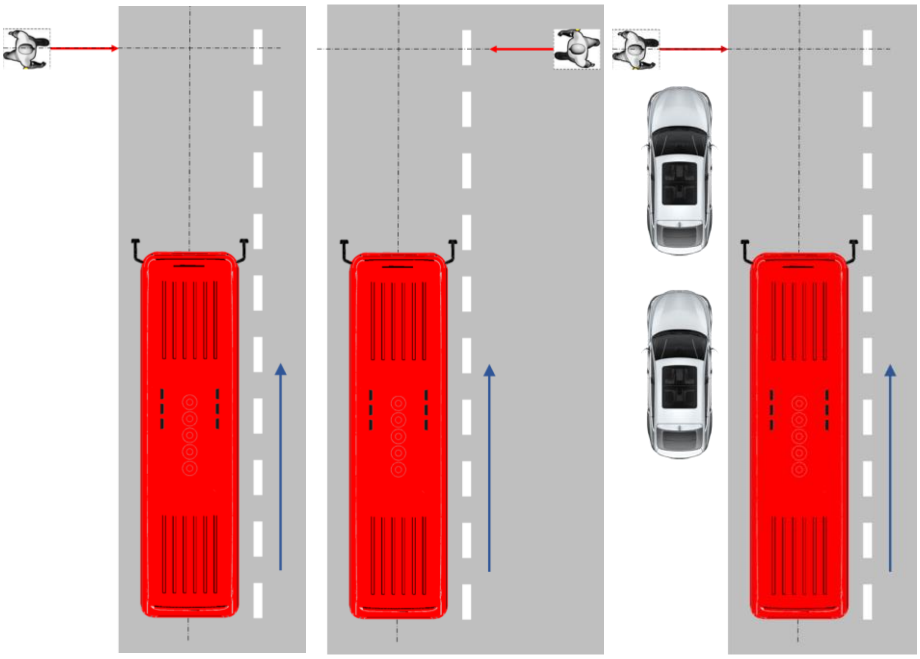


Figure 24: VRU crossing
(left: adult walking from nearside; middle: adult running from farside; right: child running from nearside with obscuration)

All tests will be undertaken in daylight. The nearside adult tests described above will be repeated in night-time conditions because the collision statistics show that performance at night in street lit conditions will be an important feature of an effective system. The only night-time tests of AEB formalised in a procedure are the Euro NCAP ones and these have been copied exactly. However, if the streetlighting in London results in substantially less illumination of pedestrians than would be found under Euro NCAP test, then doing well in the tests will not necessarily translate to good night-time performance in service. Similarly, any policy to switch off more street lights than was the case in the period the collision data covered (up to 2016) could potentially affect AEB performance, if the system in question is dependent on light level.

7.2.3 Longitudinal cyclist tests

The AEB system will be assessed in two longitudinal scenarios, with the cyclists travelling in line with the 50% impact point (i.e. in line with the middle of the bus) and the 25% impact point. This is illustrated in Figure 25.

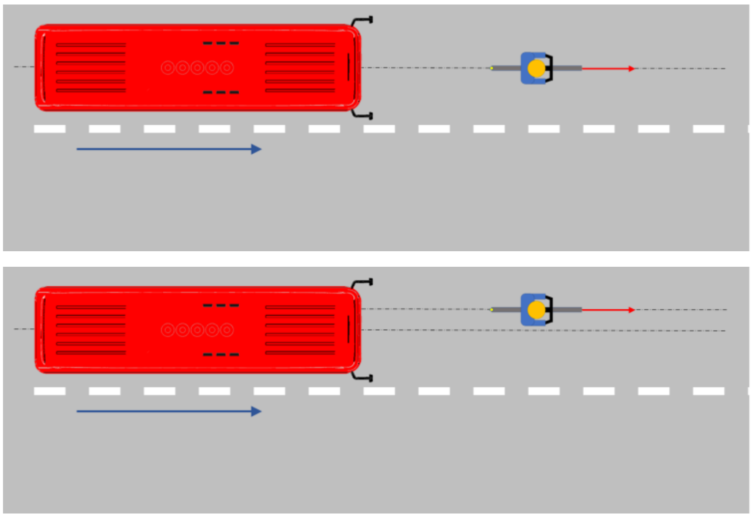


Figure 25: Longitudinal cyclist tests (top: 50% impact point; bottom: 25% impact point)

7.2.4 False positive tests

The aborted crossing test has the same test geometry as the true positive test that assesses an adult walking from the nearside. However, instead of crossing into the path of the bus, the VRU dummy stops at lateral distances between 0.6m and 0.9m away from the path of the bus (Figure 26).

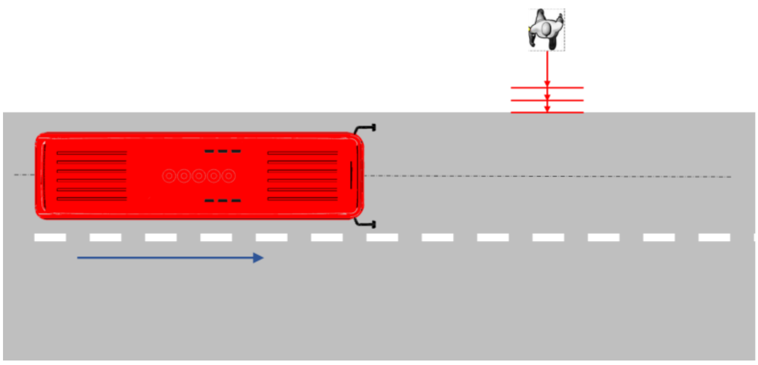


Figure 26: Aborted crossing – false positive test

For the bus stop test, the pedestrian remains stationary and the bus is required to follow an "s-bend" path that simulates the vehicle pulling into a bus stop or changing lane to the nearside and passes the pedestrian with a lateral distance of 0.2m between the pedestrian and the front-nearside corner of the bus (Figure 27).

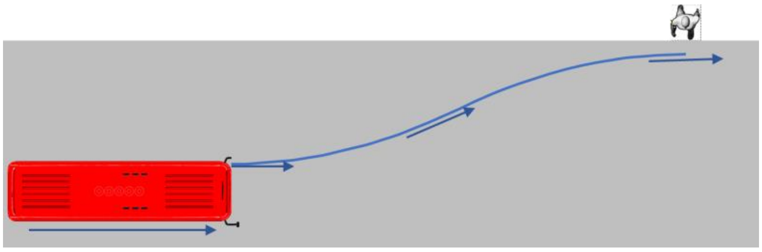


Figure 27: Bus stop test – false positive

For the true positive bus stop test (Figure 28), the test geometry is the same as for the false positive test except that the pedestrian movement is configured such that it is on a collision course with the centre of the front of the bus (nominal impact point = 50%).

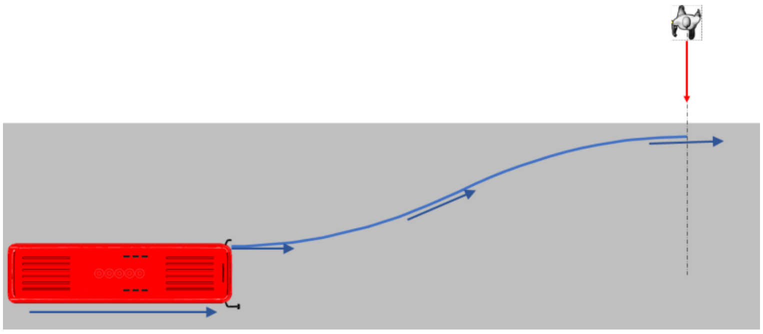


Figure 28: Bus stop test – true positive

7.3 Additional specifications

The test protocol described above will be capable of stand-alone use to assess AEB for buses in almost any context. To tie it into TfLs wider BSS and procurement process, the requirement to use the protocol to assess any vehicle fitted with AEB, or indeed to make it an essential requirement of procurement, must be written into TfLs 'Bus Vehicle Specification' document. Text for this has been drafted. In addition to this, text has also been drafted for this document that would allow TfL to require any system to provide activation information to a recording system (e.g. existing CCTV units) and to specify a minimum standard for real world false positive rates.

The rationale for an additional false positive requirement is that previously discussed: two tests cannot guarantee adequate real-world performance where an almost infinite variety of driving situations may be encountered. Such a requirement could be self-certified by manufacturers or TfL could choose to require manufacturers to present evidence to them that this had been achieved. If the latter route is chosen, then TfL approval personnel will need to understand the difference between a good evidence base and a poor one.

Each manufacturer of an AEB system is likely to have their own way of verifying their systems. However, all are likely to include the following elements:

- A definition of what they consider to be a 'false' activation
- A large quantity of data from real world driving with the actual system measuring what it would do
- A large quantity of simulated driving

Earlier sections of this report discussed the definitions of false activations in some detail. Where TfL define this to be is at their discretion. However, it will be important to identify whether the supplier in any given case is identifying any situation where the AEB activates slightly earlier than a skilled and alert driver would as false, or at the other extreme, only identifying incidences where no other road user is in view as false.

In general, it is unlikely that a bespoke AEB will be developed from scratch for the bus market: the sales volumes are too small. The systems used will have been developed initially for other vehicle types (e.g. cars or trucks), adapted for buses generically, then tuned specifically for the make and model of bus in question. Thus, a well-developed system would be expected to have undergone very large quantities of real road testing, probably millions of kms, at least in one state of tune, even if that is for one or more different vehicles. This should establish a false positive rate generically for the overall system.

However, this is not directly relevant to the specific application of the system for any given bus make/model. Thus, it is also important to have evidence that it still achieves at least that performance in this specific state of tune. So, in this case, you might also expect millions of kilometres of data in order to establish a rate of false positives, but this could be achieved by simulated driving. It will be important to ensure that it is a high-fidelity simulation, for example it is feeding data into the simulation that has been recorded by similar sensors in real road mileage.

In addition to this, you would want the simulations above to be validated. It would, therefore, be expected that for every variant where the system is effectively in a different state of tune, that enough real-world distance has been driven to be sure that it can drive the minimum distance at least once without a false activation.

In all the above situations, it will be important to ensure that the real or simulated driving undertaken is broadly representative of the type of traffic conditions expected in service in London. Thus, for example motorway mileage would be rare and should not be a substantial proportion of the verification mileage. However, in assessing this it is also important to remember that London bus routes do cover a range of different driving environments: a significant proportion of distance will be undertaken outside of central London conditions in more suburban conditions.

8 Quantifying the casualty effects of AEB on buses

8.1 Introduction

There is considerable experimental evidence of both the benefits of AEB for collision partners and of the disbenefits that heavy braking can cause for standing passengers and seated-but-unrestrained passengers on buses. The aim of this section is to quantify those numerically in terms of changes to the casualty populations likely to be affected and to study the balance between the braking strategy employed within the AEB and the outcomes to see if an optimum level exists that maximises net benefits. The casualty estimates presented in this section are based on the baseline year of 2018 only and assume that the entire TfL fleet is fitted with the relevant AEB tuning concept. Estimates covering the full 12-year analysis period are presented in the cost-benefit analysis section (Section 9).

8.1.1 AEB strategies

The analysis was based on consideration of different concepts for the tuning of an AEB for different priorities:

- AEB_{max}: AEB system is tuned to brake at whatever deceleration is required to maximise the chance of avoiding collision, right up to the maximum value the brake system can deliver;
- AEB_{cap5}: AEB system is tuned to cap braking at lower deceleration rates, compromising the collision avoidance potential in order to reduce the chance of causing additional injury to standing and unrestrained seated bus occupants, over and above that which already occurs with driver-controlled braking;
- AEB_{cap7}: AEB system is tuned to brake at a deceleration rate higher than AEB_{cap5} but below the maximum possible deceleration achieved by AEB_{max}. This approach accepts some of the potential increase in risk to bus occupants in favour of reducing the degree to which a deceleration cap compromises the protection of collision partners.

In consideration of each of the above scenarios, it has been considered that the timing of the brake intervention is fixed and is a function of the ability of the sensors, decision algorithms, the need to avoid false positives and the response times of the brake system hardware. It is only the maximum deceleration, and hence achievable speed reduction in a given situation, that is varied. An AEB_{max} system would be expected to employ a more aggressive braking strategy whereby it would apply a maximum level of deceleration. For this analysis it has been assumed that maximum level of deceleration would be 9 m/s^2, which is in line with the highest levels of deceleration observed during the system effectiveness tests (see section 4).

For the AEB_{cap5} and AEB_{cap7} systems, a less aggressive braking strategy would be expected. Thus, calculations of benefits and risks were made with a range of lower accelerations, such that a level that still produced significant speed reduction benefits with low occupant risks could be chosen. Preliminary analysis suggested that 5 m/s^2 might be a suitable maximum for the AEB_{cap5} strategy and 7 m/s^2 would offer good opportunity achieve a more balanced risk for the AEB_{cap7} system.

In consideration of all the above permutations, it is important to remember that the AEB cannot apply any greater braking than a bus driver applying the brake pedal as hard and fast as is humanly possible.

8.1.2 Classification of system activation and related benefits / disbenefits

The analysis was structured to divide consideration of the AEB systems according to the definitions of true and false positive and negative activations as discussed in section 4.2. For the false negative and true negative classifications, the AEB system would not activate. There would be no benefit from collision avoidance/mitigation and there would be no disbenefit from additional braking events. This represents no change to the performance of the current fleet and so these classifications have not been studied in detail.

For true positive activations, the types of AEB under consideration could potentially activate in different types of collision scenarios; offering a casualty saving by avoiding or mitigating the severity of a collision, and/or increasing the risk of injury to bus occupants because of heavier braking. The STATS19 database, the bus fatal database developed by (Edwards, et al., 2017) and an analysis of a bus operators incident log and CCTV footage have been used alongside data compiled within the system verification and road trial parts of this project to estimate the likely effect of casualty numbers as a result of fitting AEB.

False Positive incidents represent cases in which the AEB system activates when it should not have done so. The effect of such incidents has been estimated by analysing the typical bus occupant injury outcome of non-collision incidents caused by vehicle braking (Incident Reporting Information System (IRIS) data and operator CCTV data) and estimates of the number of false positive events that might be expected from a fully developed production-level AEB system.

An overview illustration of how the analysis works is shown in Figure 29, below. Green arrows indicate the beneficial effects of selected true positive interventions, amber arrows indicate examples of where true positive interventions may risk causing disbenefits and red arrows show examples of where false positive interventions will cause disbenefits.

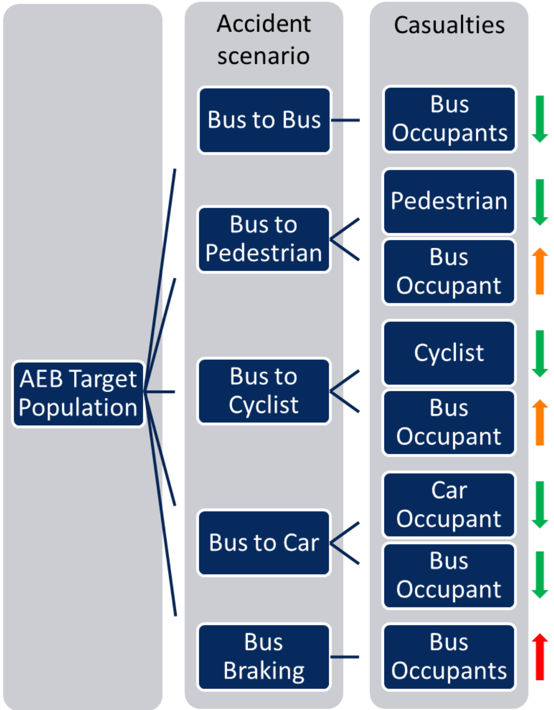


Figure 29: Illustration of the potential effects of AEB and how they have been analysed

Each of the individual analyses is described in the following subsections.

8.2 True Positive analysis

The true positive effectiveness of each AEB system has been assessed using a case by case review of the sample of London fatalities completed in the first phase of this research and the sample of mainly lower severity incidents obtained from a review of bus operator CCTV records. In each case, calculations and engineering judgments were made as to whether the system was likely to have avoided the collision, reduced the impact speed or whether in fact it would have been unable to help in the given circumstances. The ability of the CCTV data in many cases to accurately define the moment the pedestrian became recognisable as a threat, the moment the driver braked, and the amount of braking applied, was a major advantage over many other studies relying only on approximations and judgement from traditional collision reconstruction.

The assumption was made that the above samples were broadly representative of the STATS19 data set and so the estimated effect identified in those samples was applied to a similar data set from STATS19 to estimate the casualty savings that could be expected within London each year. The STATS19 data was limited to two-vehicle incidents (e.g. bus vs. pedestrian, bus vs. cyclist, bus vs. car or bus) because it becomes very difficult to assess from the available STATS19 data what has happened in multi vehicle collisions such that it is unclear if particular safety interventions will be effective in them.

For cases where it was determined that AEB would likely have mitigated the severity of the injuries, the severity of the injuries was always reduced by one level; e.g. a fatality always became a serious injury and a serious injury always became a slight injury. This is likely a conservative estimate as it is possible that some of the fatalities may have been mitigated to a slight injury.

8.2.1 Car Occupant casualties

For bus-to-car incidents, the following scenarios were considered relevant:

- The bus was going ahead, starting off, slowing or overtaking a static vehicle to its farside;
- The car was going ahead, starting off, slowing, overtaking a static vehicle to its farside, waiting to turn or being held up;
- Collision occurred between the front of the bus and the rear of the car.

There were only four fatal incidents identified from the detailed database of fatalities. All the incidents were caused by the actions of the car driver and even if the speed of the bus had been reduced to zero it was considered unlikely that it would have mitigated the severity. Therefore, it has been estimated that there would be no benefit to fatal car occupant casualties from the fitment of AEB. This likely represents an underestimate because analysis of the STATS19 data for GB showed that some fatalities do occur in relevant collision groups such that at some point it is likely that it will occur in London.

Fourteen non-fatal car occupant casualties were identified from the bus operator's CCTV records. Many of these involved a car overtaking a bus and then slowing to turn into a side road resulting in the bus striking the rear of the car as it did so. In most of these cases the driver either reacted quite late to the situation and/or did not apply maximum braking and so it was considered that AEB could offer benefit in such situations. Overall it was estimated that a collision could have been avoided in between two and seven cases (14% - 50%) depending on the performance level of the AEB system. In addition, it was estimated that the severity could have been mitigated for between zero and four cases (0% - 29%).

Applying these potential casualty reductions to the relevant casualties in the STATS19 dataset produced an estimated casualty saving of between three and 12 casualties per year (Table 12). These would mainly have been slightly injured and, overall, the low number of casualties to car occupants is likely to reflect both relatively low speeds in London and the high level of protection offered by modern passenger cars.

Table 12: Estimated annual average casualty savings for car occupants in collisions with a bus equipped with AEB. Based on 2018 baseline data

AEB Performance	Fatal	Serious	Slight	Total
AEB_{max} (9m/s²)	0.0 - 0.0	0.4 - 0.5	10.3 - 12.0	10.7 - 12.5
AEB_{cap5} (5m/s²)	0.0 - 0.0	0.4 - 0.4	3.2 - 6.7	3.6 - 7.1
AEB_{cap7} (7m/s²)	0.0 - 0.0	0.4 - 0.5	8.4 - 8.5	8.8 - 9.0

8.2.2 Pedestrian casualties

For bus-to-pedestrian incidents, the following scenarios were considered relevant:

- The bus was going ahead, starting off, slowing or overtaking a static vehicle to its farside;
- The pedestrian was crossing the road from either the left or right side;
- Collision occurred between the front of the bus and the pedestrian.

A total of 21 incidents were identified from the detailed database of fatalities that fitted the collision scenarios described above. Many of these involved a pedestrian stepping out from the pavement unexpectedly or without looking with the driver reacting, on average, less than half a second before impact. It was determined that the fitment of AEB could have potentially prevented between two and ten casualties (10% - 48%), predominately from the improved reaction time offered by the AEB system. It was also determined that the severity of a further three to nine casualties (14% - 43%) could have been reduced.

From the bus operator's CCTV records, a total of 27 non-fatal incidents were identified. On average the time to collision (TTC) when the pedestrian would have first become recognisable as a collision risk was two seconds prior to impact, with the average driver reaction time occurring 1.1 seconds before impact. For these cases it was estimated that between 13 and 24 casualties (48% - 89%) could have been avoided, and the severity of another one-to-eleven cases (4%-41%) could have been reduced.

Analysis of the STATS19 records showed that between 2006 and 2015 there were, on average, 392 pedestrian casualties in collisions involving at least one London bus each year, 11 of which proved fatal. Of these, four fatalities, 36 serious injuries and 101 slight pedestrian injuries per year arose from incidents involving a bus where the bus was going ahead, slowing or moving off from rest, and where the pedestrian was crossing the road and struck the front of the bus.

By applying the potential casualty savings evident in the detailed data samples to the STATS19 data it was estimated that fitting an AEB system would be expected to prevent 2-3 pedestrian fatalities, 29-33 serious, and 34-89 slight casualties per year (Table 13).

Table 13: Estimated annual average casualty savings for pedestrians in collisions with a bus equipped with AEB. Based on 2018 baseline data

AEB Performance	Fatal	Serious	Slight	Total
AEB$_{max}$ (9m/s²)	2.6 - 2.6	32.5 - 32.5	83.4 - 88.5	118.4 - 123.5
AEB$_{cap5}$ (5m/s²)	2.2 - 2.2	29.9 - 30.5	34.1 - 69.5	66.2 - 102.3
AEB$_{cap7}$ (7m/s²)	2.4 - 2.4	30.5 - 30.9	74.6 - 79.7	107.5 - 113.0

8.2.3 Cyclist casualties

For bus-to-cyclist incidents, the following scenarios were considered relevant:

- Both the bus and cyclist were going ahead, starting off, slowing or overtaking a static vehicle to the farside;
- Collision occurred between the front of the bus and the rear of the cyclist.

Within the detailed database of fatalities there were no incidents identified that fitted the collision scenarios described above. This correlates well with the STATS19 data which also shows that there were no cyclist fatalities in such scenarios between 2006 and 2015.

The only fatal collisions within the detailed database in which a cyclist struck the front of a bus involved a cyclist riding on the pavement before crossing and a fallen cyclist lying in the road.

STATS 19 data show that there were three cyclist fatalities in the 10-year period to 2015 where the bus turned left, and the cyclist was either going straight ahead or ‘undertaking’ on the nearside of the bus. However, current generations of AEB use forward looking sensors only and so cannot influence these collisions. This may change in future and at least one tier one supplier is known to be working on a system that works in left turn/nearside collisions in the truck market.

Incidents in which a cyclist crossed the road in front of the bus were not considered relevant because the speed of the cyclist would mean that the AEB had very little time to track the cyclist within the range of its sensors and take action before the cyclist had cleared the path of the bus. The crossing cyclist described above was also partially obscured by an advertising sign which would have further limited the time at which the AEB could detect the cyclist. For the case where the cyclist had fallen off his bike, was laying in the road and was subsequently run over by the bus; it was assumed that the AEB would not have been able to detect the person lying in the road as a cyclist/pedestrian and so AEB would not have been effective in this case.

Four non-fatal incidents were identified from the bus operator’s CCTV records. On average the TTC at the moment the cyclist became recognisable as being on an imminent collision course was just under two seconds. The average time at which the driver braked was 0.3 seconds before impact, suggesting that AEB could offer benefits from an improved reaction time. An analysis of these incidents estimated that between two and three casualties (50% -75%) could have been avoided with the fitment of AEB with the severity reduced for a further 0 – 1 casualty (0% - 25%).

By applying the potential casualty savings evident in the detailed data samples to the STATS19 data it was estimated that fitting an AEB system would be expected to prevent one serious casualty every 2 years and between 4 and 6 slightly injured cyclist casualties per year (Table 14).

Table 14: Estimated annual average casualty savings for cyclists in collisions with a bus equipped with AEB. Based on 2018 baseline data

AEB Performance	Fatal	Serious	Slight	Total
AEB_{max} (9m/s²)	0.0 - 0.0	0.5 - 0.5	5.3 - 5.3	5.7 - 5.7
AEB_{cap5} (5m/s²)	0.0 - 0.0	0.5 - 0.5	3.4 - 5.3	3.8 - 5.7
AEB_{cap7} (7m/s²)	0.0 - 0.0	0.5 - 0.5	3.4 - 5.3	3.8 - 5.7

8.2.4 Bus occupant casualties

The effect on the number of bus occupant casualties has been sub-divided into groups relevant to the collision partner.

8.2.4.1 Bus-to-car incidents

In addition to the benefit to car occupants described in section 8.2.1, there are potential benefits to bus occupants. When a bus hits a car, it could potentially produce deceleration levels that are significantly higher than seen under braking. Thus, avoiding such a collision with heavy braking can reduce the peak deceleration experienced by occupants of the bus and reduce their injury risk.

The number of bus-to-car collisions avoided is, by definition, the same whether it is the car occupants injured or the bus occupants injured in those incidents that are being studied. Thus, the 'avoidance' element of the benefits will be identical to those calculated for the car occupants above. In theory, the effect on mitigation of injury severity may be different for the bus and car occupants. However, there was very little information available with which to quantify this difference and this is a low severity collision type for both casualty groups. Car occupants will see the higher changes in velocity and accelerations but benefit from much higher standards of occupant protection. Bus occupants will see low changes in velocity and acceleration but have little occupant protection. In the absence of specific information, it has simply been assumed that the overall effectiveness of AEB for bus occupants injured in collisions with cars, is the same as that estimated for the car occupants, namely avoiding (14% - 50%) of casualties and mitigating the severity of (0% - 29%). The percentage effectiveness estimates were then applied to the relevant bus occupant casualties in the STATS19 dataset. The analysis resulted in an estimated casualty saving of between three and ten bus occupant casualties per year (Table 15).

Table 15: Estimated annual average casualty savings for bus occupants (on board an AEB-equipped bus) in collisions with a car. Based on 2018 baseline data

AEB Performance	Fatal	Serious	Slight	Total
AEB_{max} (9m/s²)	0.0 - 0.0	0.3 - 0.4	8.1 - 9.5	8.4 - 9.8
AEB_{cap5} (5m/s²)	0.0 - 0.0	0.3 - 0.3	2.5 - 5.3	2.8 - 5.6
AEB_{cap7} (7m/s²)	0.0 - 0.0	0.3 - 0.4	6.7 - 6.7	7.0 - 7.1

8.2.4.2 Bus-to-pedestrian incidents

In comparing AEB and human braking, the main advantage of automated braking in this situation is that the reaction time can be substantially less than a ‘typical’ human reaction time of between around 0.75s and 1.5s. However, the magnitude of braking and how quickly it builds up to maximum depends mainly on physical characteristics of the braking system and tyres. Thus, the automated braking cannot produce any greater deceleration than a skilled human driver could generate, it just produces it earlier.

Human braking performance is, however, highly variable. An AEB system can brake no harder than the best human driver. However, most human drivers do not achieve the same braking performance as the best human driver. Therefore, in some circumstances, an AEB system will brake harder than the average human driver. This forms an additional benefit of the system but does create the possibility that it will increase the frequency or severity of injuries on board the bus, even if the system is not held liable for that increase because it only does the same as the best human driver.

An AEB system will only brake harder than the driver if its sensors determine a collision will occur and the driver does not exploit the maximum braking available to them. Thus, this risk only exists in instances where a collision would have occurred with normal human braking. Based on the number of pedestrian casualties as shown in Table 13, and an average London bus occupancy of 19.3[5] the total number of bus occupants on board at the time of the pedestrian incidents was estimated. This number represents the total number of bus occupants at risk of injury during the relevant bus-to-pedestrian incidents. If AEB were fitted and increased average braking acceleration during those events, then it is possible that a greater proportion of the bus occupants at risk would have been injured.

A proportion of CCTV records involving passenger injury incidents included data about the vehicle acceleration. The range of peak acceleration values recorded for braking incidents ranged from $-1.4m/s^2$ to $-8.7m/s^2$. It was noted that in most incidents only a small proportion of the occupants on board fell, so confirmation of the effect was sought by analysing the proportion of all occupants on board the bus that ended up injured by the acceleration level involved. The peak longitudinal decelerations were grouped into ten categories and the average percent of occupants injured within each category calculated. For example, Figure 30 below shows that for incidents having a peak deceleration between $6\text{-}7m/s^2$ an average of 2.5% of occupants were injured. The data in this sample includes data from collision incidents and in some of those collision incidents, the only injury was to the third party outside the vehicle, with no passenger injuries. Thus, the average proportion of occupants injured includes some cases where the proportion is 0% and some where it is much higher than average. Figure 30 confirms the expected trend of increasing acceleration resulting in more casualties.

[5] Source: DfT Bus Statistics Table BUS0304 data for London in 2016/17. Note that the equivalent figure for England excluding London is 9.5 suggesting any risk to occupants would be substantially lower outside of London.

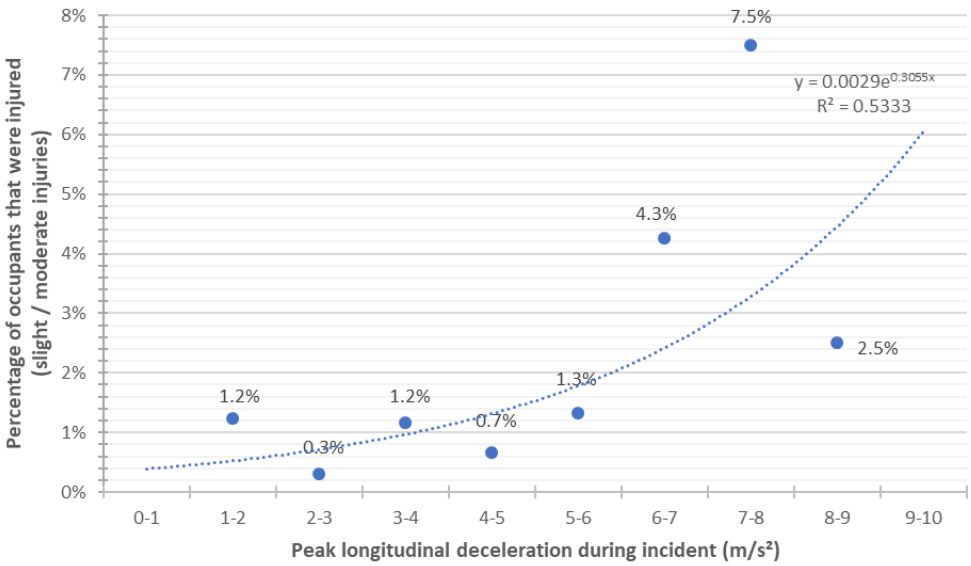


Figure 30: Relationship between percentage of bus occupants injured and the peak longitudinal deceleration experienced

The acceleration information above relates to all incidents where bus occupants were injured and acceleration data was available, regardless of whether the fall/injury occurred in a collision with a pedestrian, cyclist or a non-collision incident. When the data was restricted to bus-to-pedestrian collisions, the average value of driver-applied deceleration was $2.9m/s^2$. This falls within the $2\text{-}3m/s^2$ category as shown in Figure 30 and based on the trend line the average proportion of occupants injured is estimated as 0.7%.

For each of the AEB performance levels (AEB_{max}, AEB_{cap5}, AEB_{cap7}) the deceleration that could be expected from the AEB system was calculated, based on the assumption that the timing of the intervention was the same for each AEB performance level, only the deceleration changed. For the specific bus-to-pedestrian cases reviewed it was estimated that the AEB would result in a deceleration of between $3.0m/s^2$ and $5.5m/s^2$ which, based on the relationship shown in Figure 30 would be expected to increase the proportion of occupants injured to between 1.0% and 1.8%.

The difference between the proportion of occupants injured from AEB braking to the proportion of occupants injured during driver-applied deceleration represents an additional risk to bus occupants.

By applying this change to all bus occupants on board at the time of the pedestrian incidents, the total number of bus occupant injuries was estimated. It was assumed that the severity breakdown of these casualties matched the severity breakdown of bus occupant injuries in bus-to-pedestrian collisions as reported by STATS19. The resulting casualty risk is shown in Table 16.

Table 16: Estimated annual average casualty increase for bus occupants (on board an AEB-equipped bus) in collisions with a pedestrian, based on 2018 baseline data

AEB Performance	Fatal	Serious	Slight	Total
AEB_{max} (9m/s²)	0.0 - 0.0	0.0 - 0.0	5.9 - 26.9	5.9 - 26.9
AEB_{cap5} (5m/s²)	0.0 - 0.0	0.0 - 0.0	3.3 - 12.5	3.3 - 12.5
AEB_{cap7} (7m/s²)	0.0 - 0.0	0.0 - 0.0	5.2 - 24.1	5.2 - 24.1

Bus-to-cyclist incidents

The risk to bus occupants in this crash type is in principle the same as for pedestrian incidents as described above. However, the number of cyclist incidents where automated braking may apply greater acceleration than a human driver will be different. For example, it was estimated that the average value of driver-applied deceleration during the bus-to-cyclist incidents was 2.2m/s² and that the AEB would result in a deceleration of between 2.8m/s² and 5.5m/s².

The difference between the proportion of occupants injured from AEB braking to the proportion of occupants injured during driver braking again represents an additional risk to bus occupants which was quantified by applying this change to all bus occupants on board at the time of the relevant bus-to-cyclist incidents. The resulting casualty disbenefit is shown in Table 17.

Table 17: Estimated annual average casualty increase for bus occupants (on board an AEB-equipped bus) in collisions with a cyclist, based on 2018 baseline data

AEB Performance	Fatal	Serious	Slight	Total
AEB_{max} (9m/s²)	0.0 - 0.0	0.0 - 0.0	0.3 - 1.2	0.3 - 1.2
AEB_{cap5} (5m/s²)	0.0 - 0.0	0.0 - 0.0	0.1 - 0.7	0.1 - 0.7
AEB_{cap7} (7m/s²)	0.0 - 0.0	0.0 - 0.0	0.2 - 1.2	0.2 - 1.2

Bus-front to bus-rear incidents

For bus-front to bus-rear incidents, the same scenarios that were considered relevant for bus-to-car incidents were selected, namely:

- The striking bus was going ahead, starting off, slowing or overtaking a static vehicle to its farside;
- The target bus was going ahead, starting off, slowing, overtaking a static vehicle to its farside, waiting to turn or being held up;
- Collision occurred between the front of the striking bus and the rear of the target bus.

STATS19 data showed that there were no fatal incidents within the last 10 years in Great Britain and as such it has been estimated that there would be no benefit to fatal bus occupant casualties from the fitment of AEB in bus-front to bus-rear collisions.

Analysis of the operator's CCTV records identified only one bus-front to bus-rear incident. There were a further three cases where another bus (presumably run by a different operator) had struck the rear of one of the operator's bus, but the database did not contain enough information about the incidents to make a judgement about the effectiveness of AEB. Using just a single incident to estimate the effectiveness of AEB would result in an effectiveness of 0% or 100% whereas the true effectiveness will lie somewhere in between these extremes. For this reason, it was decided to use the estimated effectiveness of bus-front to car-rear incidents since both target vehicles represent large objects that could be sensed by the radar and camera sensors.

The potential casualty reductions of avoiding 14% - 50% of non-fatal incidents and mitigating the severity of a further 0% - 29% were applied to the relevant casualties in the STATS19 dataset. This produced an estimated casualty saving of between three and ten casualties per year (Table 18).

Table 18: Estimated annual average casualty savings for bus occupants (on board an AEB-equipped bus) in front-to-rear collisions with another bus, based on 2018 baseline data

AEB Performance	Fatal	Serious	Slight	Total
AEB$_{max}$ (9m/s^2)	0.0 - 0.0	0.4 - 0.5	8.4 - 9.8	8.8 - 10.3
AEB$_{cap5}$ (5m/s^2)	0.0 - 0.0	0.4 - 0.4	2.5 - 5.5	2.9 - 5.9
AEB$_{cap7}$ (7m/s^2)	0.0 - 0.0	0.4 - 0.5	6.9 - 6.9	7.3 - 7.4

8.2.5 Net effect of true positive analysis

The sum of each of the changes discussed above is presented below in Table 19 and Table 20.

Table 19: Total estimated annual casualty benefit of true positive analysis (sum of Table 12, Table 13,Table 14, Table 15, Table 18)

AEB Performance	Fatal	Serious	Slight	Total
AEB$_{max}$ (9m/s^2)	2.6 - 2.6	33.9 - 34.1	113.4 - 122.6	149.9 - 159.3
AEB$_{cap5}$ (5m/s^2)	2.2 - 2.2	31.4 - 32.0	45.0 - 91.0	78.6 - 125.1
AEB$_{cap7}$ (7m/s^2)	2.4 - 2.4	32.0 - 32.5	98.3 - 105.4	132.6 - 140.3

Table 20: Total estimated annual casualty disbenefit of true positive analysis (sum of Table 16, Table 17)

AEB Performance	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	0.0	-	0.0	0.0	-	0.0	6.2	-	28.1	6.2	-	28.1
AEB$_{cap5}$ (5m/s²)	0.0	-	0.0	0.0	-	0.0	3.4	-	13.1	3.4	-	13.1
AEB$_{cap7}$ (7m/s²)	0.0	-	0.0	0.0	-	0.0	5.4	-	25.3	5.4	-	25.3

Table 21: Total estimated annual net benefit of true positive analysis (sum of Table 19, Table 20)

AEB Performance	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	2.6	-	2.6	33.9	-	34.1	85.4	-	116.4	121.9	-	153.1
AEB$_{cap5}$ (5m/s²)	2.2	-	2.2	31.4	-	32.0	31.9	-	87.6	65.5	-	121.8
AEB$_{cap7}$ (7m/s²)	2.4	-	2.4	32.0	-	32.5	73.0	-	100.0	107.3	-	134.9

Note: The upper level of net effect has been calculated by comparing the upper level of benefit to the lower level of risk, and the lower level of net effect has been calculated by comparing the lower level of benefits to the upper level of risk.

Table 21 shows that there is an expected net benefit of between 65 and 153 casualties per year, depending on the performance level of the AEB system. Applying the standard Department for Transport (DfT) economic values for the prevention of those casualties suggests a monetised benefit of between £11.0m and £13.7m per year.

8.3 False positive analysis

If the AEB system were to apply braking in a situation where most careful competent and alert human drivers would not have applied braking, it can be considered a false positive. In this situation, the braking creates a risk of injury to bus occupants, and potentially other road users though they should still be travelling at a distance to be able to avoid collision with the braking bus. A subtle but important distinction is that this is different from a situation where the system applies braking in response to a recognisable threat of collision but that this is applied a little too early. Such interventions can annoy the driver but are much less likely to cause a direct injury risk because there was a genuine need for braking, whether human or system applied.

At this stage of the research, and of the development of the prototype system that has been studied, the eventual false positive rate of a production London bus system is fundamentally unknown. No published information has been identified that can confirm the typical false positive rate experienced by comparable systems already in production. On this basis it was decided that the core analysis should use a range of assumed values that might be suitable for use as a minimum standard if TfL implemented AEB in the BSS. It was assumed that the rate would be between 600,000km and 1 million km of driving with no false positive brake activations.

Applying these figures to the total number of bus vehicle km travelled in London each year (490million[6]) results in an estimate of between 490 and 817 false positive braking events per year in London.

During the one-week road trial covering 400km on five different bus routes, undertaken as part of this project (section 6.2), the number of deceleration events that occurred during the trial were recorded and grouped by the peak deceleration. The trial showed that 98% of all braking events occurred below 2m/s², with no events exceeding a peak deceleration of 3.5m/s². The reason for this is purely the relatively small sample size. It is obvious that full emergency stops do occur in normal service, they are certainly recorded in incident data and almost certainly occur sometimes where there is no incident. However, these will clearly be very rare in comparison to lesser brake applications.

The number of brake events by deceleration recorded during the road trial have been extrapolated to suggest appropriate levels that might reasonably be found in a much larger trial (Figure 31).

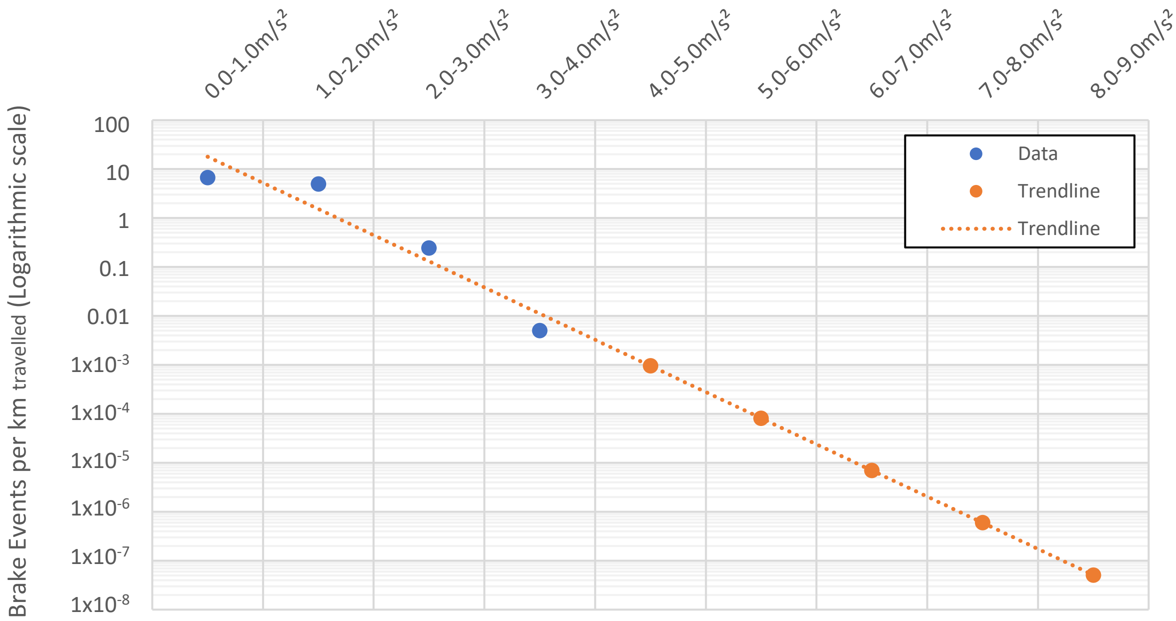


Figure 31: AEB road trial brake events extrapolated for higher deceleration groups

Applying these figures to the total number of bus vehicle km travelled in London each year (490million[6]) provides an estimate of the number of deceleration events

[6] Source: DfT Bus Statistics Table BUS0203b. Note TfL data suggests a total of 492.3 million bus km for 2016/17

that occur in London each year by peak deceleration (Table 22). Given the large number of buses and the distance they cover each year, this shows that braking events at high levels of deceleration are comparatively rare.

Table 22: Estimated number of deceleration events by buses in London per year

Deceleration (m/s²)	Brake events/km (rate per million km)	Brake events/year (number)
0.0-1.0m/s²	6,688,959	3,277,342,050
1.0-2.0m/s²	4,940,310	2,420,568,735
2.0-3.0m/s²	243,007	119,064,478
3.0-4.0m/s²	5,010	2,454,938
4.0-5.0m/s²	956	468,428
5.0-6.0m/s²	82	40,020
6.0-7.0m/s²	7	3,419
7.0-8.0m/s²	0.6	292
8.0-9.0m/s²	0.05	25

Data from the CCTV analysis (Figure 32) shows the proportion of casualties that occur at each acceleration level.

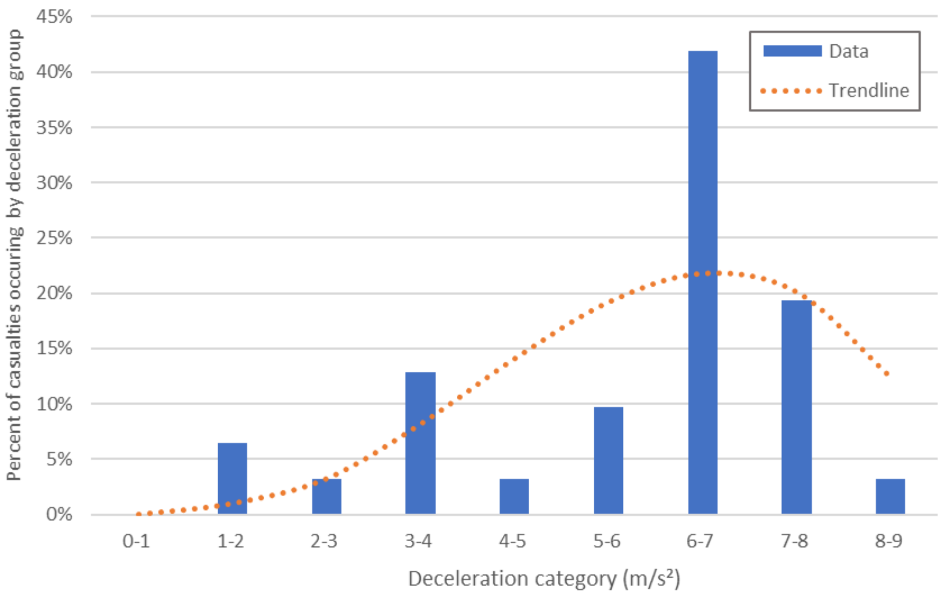


Figure 32: Proportion of bus occupant casualties that fell under braking by peak deceleration experienced during braking. Source: Analysis of CCTV records

Analysis of the IRIS database identified an average of 974 casualties per year that resulted from non-collision incidents in which braking was coded as the cause of the injuries.

These two data were combined to produce an estimate of the annual average number of casualties that occur at each braking level which was then applied to the event data (Table 22) to estimate the number of casualties per braking event at each acceleration level. The results are shown in Table 23 below.

Table 23: Estimated number of casualties per braking event by deceleration level

Deceleration (m/s^2)	Brake Events/year (number)	Casualties per deceleration event (rate)
0.0-1.0m/s²	3,277,342,050	0.00
1.0-2.0m/s²	2,420,568,735	0.000000026
2.0-3.0m/s²	119,064,478	0.00000026
3.0-4.0m/s²	2,454,938	0.000051
4.0-5.0m/s²	468,428	0.000067
5.0-6.0m/s²	40,020	0.0024
6.0-7.0m/s²	3,419	0.12
7.0-8.0m/s²	292	0.65
8.0-9.0m/s²	25	1.26

Considering the performance level of the AEB solutions under consideration (i.e. a maximum deceleration of $9m/s^2$ for AEB_{max}, $5m/s^2$ for AEB_{cap5} and $7m/s^2$ for AEB_{cap7}) the total number of casualties resulting from the false positive events was estimated.

It was assumed that the breakdown of these casualties by injury severity would match the breakdown of bus occupant casualties resulting from non-collision incidents in London, where the bus was not stationary or reversing. The resulting casualty risk is shown in Table 24.

Table 24: Total predicted increase in casualties per year as a consequence of false positives

AEB Performance	Fatal			Serious			Slight			Total		
AEB_{max} ($9m/s^2$)	0.0	-	0.5	0.0	-	26.4	0.1	-	336.2	0.1	-	363.1
AEB_{cap5} ($5m/s^2$)	0.0	-	0.0	0.002	-	0.003	0.02	-	0.04	0.02	-	0.04
AEB_{cap7} ($7m/s^2$)	0.0	-	0.0	0.0	-	2.5	0.1	-	32.0	0.1	-	34.6

Applying the standard DfT economic values for the prevention of those casualties suggests a monetised disbenefit of between £0.001m and £11.7m per year.

8.4 Overall benefit analysis

By combining the net effect of the true positive analysis and the disbenefits from the false positive analysis the overall benefit result can be estimated.

Table **25** shows the total net effect of the true positive and false positive analyses. It can be seen there would be an expected reduction in the number of fatalities and serious injuries resulting from the fitment of AEB, however there would be an increase in the number of slight injuries for the AEB_{max} variant. The increase in slight injuries is a result of the additional casualties expected from false positive events.

Table 25: Total net effect of true positive and false positive analyses (sum of Table 21, Table 24)

AEB Performance	Fatal	Serious	Slight	Total
AEB_{max} (9m/s²)	2.1 - 2.6	7.4 - 34.0	-250.8 - 116.3	-241.2 - 153.0
AEB_{cap5} (5m/s²)	2.2 - 2.2	31.4 - 32.0	31.9 - 87.6	65.5 - 121.7
AEB_{cap7} (7m/s²)	2.4 - 2.4	29.5 - 32.5	40.9 - 99.9	72.8 - 134.8

Although the overall number of casualties has increased for the AEB_{max} system, applying the standard DfT economic values for the prevention of those casualties shows that all three performance levels offer a net monetised benefit (Table 26). This is because the number of slight casualties is much higher than the number of fatalities, but the monetised value of each slight casualty is less than 1% of the monetised value of each fatality.

Table 26: Total net monetised casualty effect of true positive and false positive analyses

AEB Performance	Fatal	Serious	Slight	Total
AEB_{max} (9m/s²)	£3.9 - £4.8	£1.5 - £7.0	-£4.0 - £1.9	£1.5 - £13.7
AEB_{cap5} (5m/s²)	£4.1 - £4.1	£6.5 - £6.6	£0.5 - £1.4	£11.0 - £12.1
AEB_{cap7} (7m/s²)	£4.3 - £4.4	£6.1 - £6.7	£0.7 - £1.6	£11.1 - £12.7

8.5 Sensitivity analysis

8.5.1.1 Introduction

The analysis presented above has been based on the best estimates that could be inferred from the data that we were able to identify within the study. However, as is common in this sort of analysis, the data required for a fully robust analysis is not always available. It is, therefore, good practice to analyse the sensitivity of the results of the analysis to plausible variations in the input data used. Those input factors that have the largest influence on the results or that are shown to be capable of changing the overall conclusions of the work can then be subject to greater scrutiny to assess their robustness. Such an analysis has been undertaken for this work considering:

1. Method of calculating effectiveness from in-depth fatal collision and CCTV analysis
2. Details of characteristics of AEB intervention, e.g. TTC at brake intervention, deceleration characteristics etc.
3. Relationship between proportion of bus occupants injured and acceleration (Figure 30), considering defining trend based on use of ‘raw’ point cloud or aggregated acceleration categories, different trend line definitions, inclusion of collision data, exclusion of low volume data etc
4. Proportion of bus occupant casualties that occur in deceleration events of each category: consideration of raw data and trend line data
5. Frequency of different levels of brake applications in service and extrapolation to emergency braking levels
6. The rate of false positive activations and the deceleration levels demanded by them

The first two items affect the true positive benefit of systems to collision partners and occupants. The methods used for this are well established and the detailed data available about the collision, from the CCTV data with accelerometer values etc, and about the AEB system from the true positive testing on the test track enabled quite a robust analysis. It was found that the changes arising from different ways of looking at the data and interpreting it, did not lead to excessively large changes in results and were unlikely to materially affect the overall conclusions.

The relationship between the proportion of occupants injured at different levels of braking acceleration was based on only a small sample of relevant cases from the CCTV study. It was, therefore, possible to engineer quite significant changes in the relationship based on different ways of fitting a curve to the raw data. However, the number of brake applications on buses in London every year will be very large, and the number of non-collision injuries is very low by comparison. It is also clear from STATS 19 data that when non-collision incidents occur, the number of casualties per incident (1.13) is much lower than average occupancy (19). Furthermore, this information was used in the analysis of disbenefits to occupants in true positive activations. In this scenario, the difference in acceleration from driver-applied braking to AEB was relatively small and the number of true positive applications is small relative to the overall number of brake applications in the wider fleet. In combination, this meant that relatively large input changes did not have a substantial influence on the outcome.

However, items 4 to 6 from the list above were all found to have the potential to substantially influence the conclusions and are considered in more detail in the subsequent sections.

8.5.2 Acceleration & casualty frequency relationship

The relationship between bus occupant casualty frequency and braking acceleration was based on the same small sample of data from the CCTV analysis undertaken with one London operator. The results are reproduced in Figure 33, below.

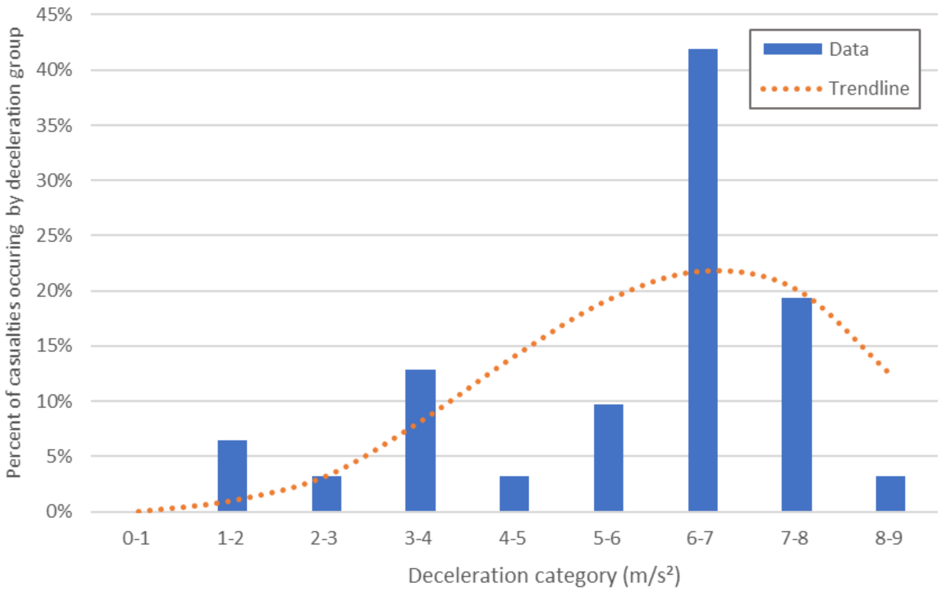


Figure 33: Proportion of bus occupant casualties arising from braking incidents by peak deceleration experienced. Source: Analysis of CCTV records

In the core analysis presented above, the base data shown by the blue bars was used, so the figures for the 5 m/s^2 AEB$_{cap5}$ system were based on the 3% of casualties occurring at 4-5 m/s^2 and the 7 m/s^2 from the 42% in the 6-7 category etc. A trend line has been added to the data and that would produce quite different values at each of the categories relevant to the different AEB systems assessed. However, even then, the correlation factor is not strong, and it would be equally possible to draw a horizontal line through the data until accelerations of up to 6 m/s^2. Above that level could be considered a completely different trend. There is a clear peak at 6 to 7 m/s^2 and a strong decline at levels above this. This may be purely attributable to driver behaviour in that few drivers are capable of fully exploiting the brakes, or that they are deliberately avoiding full braking in order to minimise risks to passengers. Discussion with operators suggests that drivers will be trained to brake gently during normal driving but would not be specifically trained to limit braking in an emergency.

However, a different interpretation of the same data is possible. The data was from a period of 2015-2017 and would have covered any age of bus in the particular operator's fleet. Thus, a significant proportion may have been quite old. TfL fleet data suggests across all operators, 36% of vehicles were seven or more years old, with 16% being ten or more years old. In general, the brakes of commercial vehicles have improved over recent years with the introduction of electronically controlled braking, disc brakes etc. In years gone by, it would not be uncommon for the maximum achievable deceleration of a bus to be in the region of 6 m/s^2, see for example (Zagorski, et al., 2013). Thus, the distribution at that point could all be drivers exploiting maximum available braking but just reflecting that the brakes of some buses in the fleet are better than others. This latter consideration would not directly affect the numbers in the analysis but would affect the interpretation, the effect of worsening risk in the 9m/s^2 AEB_{max} system is attributed to the automatic braking but may in fact be a combination of automated braking and improved maximum deceleration capability. The latter has been introduced voluntarily to the market already and should ideally be excluded from an analysis of the effects of automation. Even more relevant than this might be the alternative explanation that the lower levels of braking are maximum brake applications by the driver but limited by the available friction because the road is wet or slippery for another reason. In this case, the analysis is considering a risk of 9 m/s^2 automated braking where it would not occur due to road/weather conditions.

In order to assess the influence of reasonable and plausible changes to the distribution that might arise in a larger more robust sample of data, the core analysis was repeated using the distribution marked by the trend line in Figure 33 rather than the raw data. The results in terms of the change in the predicted increase in casualties are shown in Table 27, below.

Table 27: Change in predicted increase in casualties as a consequence of false positives based on use of raw casualty distribution compared with a trend line distribution, other variables as per core analysis

Data used	AEB Performance	Fatal			Serious			Slight			Total		
Raw	AEB_{max} (9m/s^2)	0.0	-	0.5	0.0	-	26.4	0.1	-	336.2	0.1	-	363.1
	AEB_{cap5} (5m/s^2)	0.0	-	0.0	0.002	-	0.003	0.02	-	0.04	0.02	-	0.04
	AEB_{cap7} (7m/s^2)	0.0	-	0.0	0.0	-	2.5	0.1	-	32.0	0.1	-	34.6
Trend	AEB_{max} (9m/s^2)	0.0	-	1.8	0.0	-	101.4	0.2	-	1289	0.2	-	1392.6
	AEB_{cap5} (5m/s^2)	0.0	-	0.0	0.007	-	0.012	0.09	-	0.16	0.10	-	0.17
	AEB_{cap7} (7m/s^2)	0.0	-	0.0	0.0	-	1.3	0.2	-	16.8	0.2	-	18.2

There is a dramatic difference in the results. The AEB system capable of 9 m/s^2 automated braking (AEB_{max}), for the same number of false positive activations, is predicted to cause around four times the number of casualties. In monetised terms, the disbenefit of false positives from the AEB_{max} system is increased from between £0.001m - £11.7m to between £0.003m - £44.9m, completely reversing the conclusion from a modest net benefit to a large net disbenefit. However, the effect on the AEB_{cap5} and AEB_{cap7} is small and in the case of the latter suggests an improvement in the outcome.

It should be emphasised that this is just one alternative interpretation of the data and others are possible that may improve the numbers for the high deceleration system. The main point is the large degree of sensitivity to a parameter that remains relatively weakly based, with the secondary point that conclusion changing magnitudes of effect are only exhibited for the 9 m/s^2 system. A capped maximum deceleration substantially reduces the sensitivity.

8.5.3 Frequency of different braking levels in service

Another important element of the prediction of false positive events, was the estimate of the number of braking events there were in London at different acceleration levels. In theory, it is this number of braking events, measured in the billions per year, that leads to the casualties on board the bus from braking events, which measured by IRIS data, is on average less than 1000 per year.

This data was based on a 400km road trial with no passengers on board using six drivers who regularly drove for operators, on five actual routes selected to include both high and low risk routes. The trial was reasonably well scientifically controlled, and the data was measured accurately. However, compared to the 490 million km driven in total by London buses it was a very small sample at 0.00008% of annual distance travelled. This was apparent in the fact that no situations requiring harsh braking were encountered during the trial at all. The rate at which high deceleration brake applications were likely to occur was predicted based on a trend analysis from the low-level deceleration events.

Although the correlation was strong, there will always be some error in such a prediction based on only a small number of points. In addition to this, there may have been an unavoidable systematic bias in this data: the bus drivers involved knew their driving was being recorded with lots of instrumentation and video. There were also no passengers on board and no route timetable to comply with. Despite the instructions to drive as normal, they may have adapted their behaviour consciously or unconsciously as a result.

Another variable in this data relates to the definition of braking. In the initial analysis, this was taken as meaning any significant deceleration events. This meant that the data included ‘throttle off’ events where deceleration occurred for a minimum time, even though the brake pedal was not pressed. The logic was that deceleration of around 1 m/s^2 can occur under engine braking and could theoretically cause a fall or injury, based on the experimental research, for example (De Graaf & Van Weperen, 1997). However, if in the IRIS casualty data, operators only code the cause of a fall as braking when the driver says he or she was actively braking, this might be the wrong assumption. So, the data was re-examined including only incidents where the brake pedal was actually applied. This greatly reduced the number of low deceleration events without affecting the frequency of medium deceleration events. Thus, the slope of the graph defining the relationship becomes shallower and extrapolating that graph to high levels of deceleration predicts a much higher frequency of those events. As an example, the predicted frequency of brake applications of 8 to 9 m/s^2 in the London bus fleet increases from 25 incidents to 123, almost a factor of 5. Given the constant number of casualties expected from those brake applications (derived from IRIS combined with CCTV data on the distribution of casualties by acceleration category), then this very substantially reduces the calculated casualties per brake application. It is the casualties per brake application that is applied to the predicted number of false positives per year to estimate the adverse effect of false positives. Thus, the disbenefit of false positives is also very sensitive to the way in which the number of emergency brake applications in London is calculated.

The results considering a change to ignore deceleration events not involving an actual brake application are shown in Table 28, below. Other variables are set at the same value as used in the core analysis, in particular the distribution of casualties as discussed in section 8.5.2 is set at the raw distribution.

Table 28: Effect on casualty prediction of excluding throttle off deceleration events from prediction of the rate of emergency brake applications per km in the London bus fleet

Data used	AEB Performance	Fatal			Serious			Slight			Total		
Incl all decel	AEB_{max} (9m/s²)	0.0	-	0.5	0.0	-	26.4	0.1	-	336.2	0.1	-	363.1
	AEB_{cap5} (5m/s²)	0.0	-	0.0	0.002	-	0.003	0.02	-	0.04	0.02	-	0.04
	AEB_{cap7} (7m/s²)	0.0	-	0.0	0.0	-	2.5	0.1	-	32.0	0.1	-	34.6
Brake only	AEB_{max} (9m/s²)	0.0	-	0.1	0.0	-	5.4	0.0	-	68.3	0.0	-	73.8
	AEB_{cap5} (5m/s²)	0.0	-	0.0	0.001	-	0.002	0.01	-	0.02	0.01	-	0.02
	AEB_{cap7} (7m/s²)	0.0	-	0.0	0.0	-	0.9	0.0	-	11.5	0.0	-	12.4

Changing the method in the way described substantially reduces the predicted number of casualties from false positive brake applications of 9 m/s^2 AEB to around 20% of the numbers predicted in the core case. The monetised disbenefit of this change is a reduction of the cost of false positive brake applications for the partner protecting 9 m/s^2 system from between £0.001m - £11.7m per year to between £0.001m - £2.4m per year. For the false positive rates considered in both cases (1 every 0.6 to 1.0million bus km), this does not change the overall conclusion in that it is a net benefit in each case. However, it does very substantially increase the net benefit, which for a given cost of fitting the system would substantially increase the benefit to cost ratio of the measure in the business case.

8.5.3.1 False positive rate

The false positive rates used in the core analysis were set at levels that were initially thought might prove a suitable range for minimum standards that would ensure a positive net effect for the system. There was no hard evidence available with which to predict what the actual false positive rate achievable might be. Anecdotally, discussion with suppliers of systems suggest that in a passenger car context, manufacturers will aim to achieve somewhere in the region of 450,000 to 550,000 miles (725,000 to 885,000 km) without a false positive brake intervention. However, this will be based on mixed route driving, part urban, part rural, part motorway. It is possible that within this, the false positive rate is higher in urban areas, such as those typically driven by buses. Thus, there is a risk that the range of false positive rates initially modelled may not be easily achieved in the short term. It is conceivable that, if the London bus environment proves more challenging than the passenger car one, then a false positive activation could conceivably occur every 600,000 or even 500,000 km.

However, the anecdotal information suggests that development methods are such that each system must drive a minimum distance without experiencing any false positives. The procedure is not to drive many times the threshold distance and measure how many occur to derive an actual rate per km. Thus, it is possible that a system that is shown to drive 800,000 km without a false positive would have gone on to drive much further before a false positive occurred such that using this information over-estimates the number of false positives. Equally, it is possible that manufacturers may compromise on the true positive effectiveness performance more for buses than they do for passenger cars such that the false positive rate targeted in the car industry is exceeded in buses. Equally, in the slightly longer term, manufacturers may choose to use different hardware and software approaches from the rapidly developing field of driverless technology to achieve maximum true positive benefit whilst simultaneously offering increased distance between false positives.

For that reason, an analysis of the effect of the false positive rate on the net monetised benefits of each of the different candidate systems was undertaken, across a broad range of possible values. The results are shown in Figure 34, below. Again, other variables are set at the values from the core analysis, in particular, using the ‘raw’ distribution of casualties by deceleration from the CCTV data and including throttle off deceleration events in the prediction of the frequency of emergency braking in London.

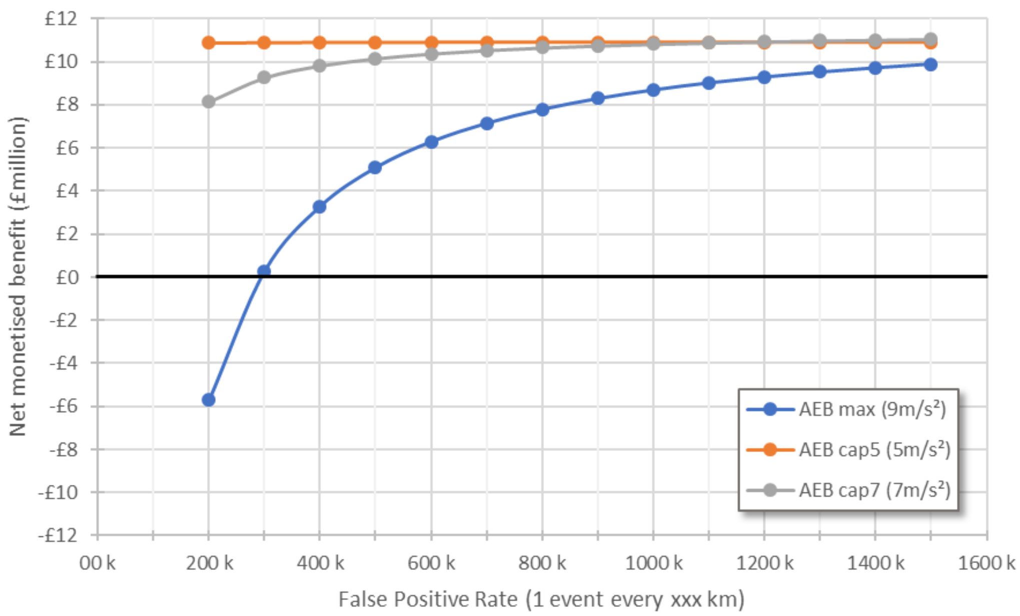


Figure 34: The effect of false positive rate on the net monetised benefit of each candidate AEB system (central prediction)

The x-axis shows the distance driven between false positives, such that the larger values to the right indicate a lower frequency of false positives. The y axis shows the net monetised effect of the system including the true positive benefits, the risks to occupants in true positive events and the risk to occupants from false positive events.

It can be seen, that the analysis predicts that if peak acceleration was capped to 5 m/s^2 then the effects are relatively insensitive to false positive rate. A cap of $7m/s^2$ introduces some sensitivity but the false positive rate needs to be considerably lower than the core case before it makes a substantial difference. However, a system that peaks at 9 m/s^2 is much more sensitive to false positive rate. This is fundamentally because of the rapid increase in risk to bus occupants at the top levels of deceleration that is apparent in the data from CCTV analysis and it must be remembered that, though a logical and plausible conclusion, is based only on a very small data sample. In reality, it is not known how the tuning process during the AEB system development will influence the resulting deceleration. It is possible tuning will eliminate all those where the urgency is high enough to demand max braking, leaving only the earlier intervention scenarios at a lower rate of deceleration, and thus introducing a lower risk. It is equally possible that the earlier intervention scenarios are easier to eliminate and the urgent ones less so, such that all remaining cases result in maximum deceleration. This will also influence the calculation above.

8.6 Analysis and interpretation

The evaluation of AEB as a potential countermeasure for London buses has confirmed that there is a significant problem to solve. Fatality statistics for London buses are dominated by pedestrians and the largest proportion of those are crossing the road in scenarios where AEB has potential benefit. Given the evidence from other sectors, there was little doubt as to the potential of AEB in true positive activations, though the difference in brake system technology (air versus hydraulic actuation) and differences in brake response time meant that significantly reduced performance was possible. The true positive testing has confirmed that substantial performance remains feasible in a bus system and full avoidance is possible from speeds relevant to a large proportion of the London bus fatality population. Applying the characteristics of both the tested AEB prototype and assumed modifications, in terms of caps on maximum deceleration, to samples of in-depth collision data (police fatal reports and operator CCTV records) suggests that the system could reduce the number of fatalities from collisions involving buses by approximately 2 or 3 per year, almost all of which would be pedestrians. This represents approximately 20% to 25% of pedestrian fatalities from collisions with London buses and approximately 12% to 14% of all fatalities from collisions involving buses in London.

It was also recognised from the start, that buses represent a unique prospect for AEB because of the existing problem where braking can cause standing occupants or unrestrained seated occupants to fall against hand rails or onto the floor with a consequent risk of injury. In most cases this injury is minor but, in some cases, can be serious and very rarely can be fatal. The concern was that if AEB braking applied heavier braking than a typical driver in true positive situations then it could increase the risk. If the system produced false positive brake applications, it would create a new risk to occupants that did not exist before and liability for those collisions might rest with the operator and manufacturer.

The analysis has confirmed the existence of this risk. Experimental research, for example (De Graaf & Van Weperen, 1997), has suggested that even very low accelerations (< 1.5 m/s^2) are enough to destabilise people. However, this research has shown that this cannot be directly related to the likelihood of an incident in service. Analysis of CCTV records certainly showed that some occupants fell at very low levels of acceleration. However, analysis of normal driving showed that this form of low-level acceleration happened all the time. It was estimated based on the road trial that there were billions of deceleration events of less than 2 m/s^2 each year on London buses. In total, IRIS records less than 1,000 bus occupant casualties attributed to vehicle braking as a cause. Of these, based on the proportions observed in the CCTV data, only around 60 would have been expected to have occurred at less than 2 m/s^2. This suggests that billions of events result in only 60 casualties – i.e. injuries at low levels of acceleration are extremely rare. By contrast, the frequency of braking events in service at higher accelerations drops logarithmically such that the highest levels occur only rarely each year. The proportion of the casualties that occur at these levels are greater. Thus, the risk per event increases enormously with acceleration but this is not linear, with the major increases not beginning until greater than 6 m/s^2. The predicted casualties per deceleration event is shown in Figure 35, below.

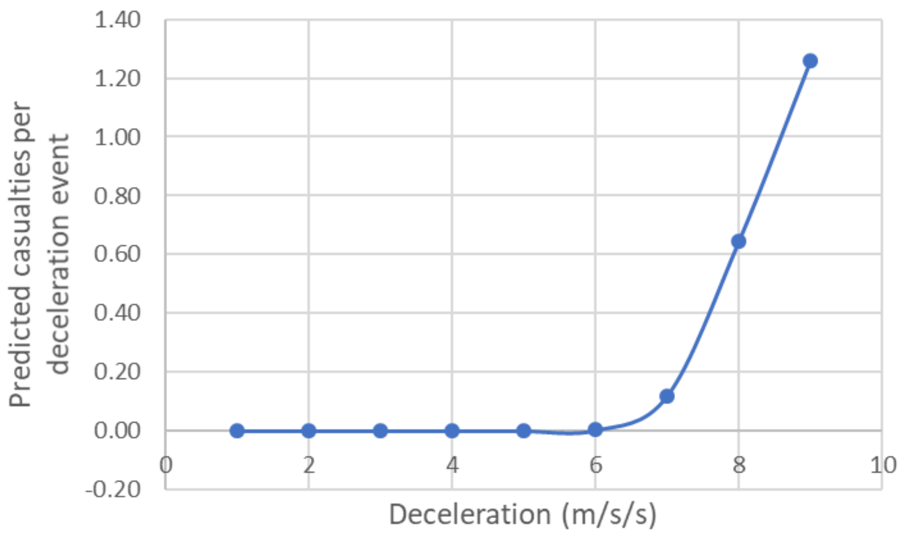


Figure 35: Predicted casualties per braking event based on input variables as per core analysis

It was found that in some true positive cases, the earlier intervention of AEB compared to a human driver, would mean that a lower deceleration was required than that applied by the driver in the collision case studied. However, if it is assumed that the driver would still respond in the same way, then the system would provide the greater of the deceleration applied by the driver or demanded by the system. If the assumption is correct, then this would lead to no change in acceleration. In other true positive cases, it was calculated that the system would apply greater deceleration than the driver did. Thus, this would result in an average increase in the acceleration levels applied but this was found to be only small. In addition to this, the number of true positive events per year of relevance is also very small compared to the frequency of moderately heavy brake applications each year. Thus, the increase in risk in true positive situations was found to be very small.

In false positive situations, all events represent a 100% increase in risk compared with no AEB system in place. The actual false positive rate expected in a production system is not known with confidence but is thought likely to be measured in the high hundreds of thousands of kms driven for each false positive brake event, only some of which would involve maximum deceleration being demanded. Given 490million bus kms driven in London in one year, this still leaves scope for a significant total number of false positive events. Thus, the risk of an increase in bus occupant casualties is also significant.

This significant increase in risk from false positives, combined with the findings in relation to the casualty risk per deceleration event (Figure 35) gives rise to consideration of the possibility of introducing AEB but limiting the maximum acceleration that could be deployed to minimise the consequences of false positives. Whilst the approach of capping the deceleration may appear to be an attractive option it will guarantee that less fatalities are prevented in true positive scenarios when it remains uncertain if the risk to bus occupants is significant (e.g. if false positive events with a peak deceleration > $7m/s^2$ are in reality very rare). In addition to this, the prototype system tested took a staged approach to braking whenever sufficient time was available to do so. This meant that the rate at which deceleration increased (sometime referred to as brake jerk) was slower than it could be. One way to get the same true positive AEB performance whilst capping peak deceleration would be to increase the brake jerk (shorten the time taken to get the to the peak). The experimental research on passenger standing stability suggested brake jerk was also an important factor in destabilising people. However, brake jerk could not be identified in the CCTV study, so it has not been possible to evaluate this in real world empirical data. Thus, there is a risk that capping peak deceleration, intended to reduce risk to occupants, may fail to reduce risk because of increased brake jerk.

The data used in several of these calculations is limited. In particular this is true of the road trial and the CCTV data analysis which were both small samples of data, and the false positive rate where there is no objective information available. A sensitivity analysis has shown that the conclusions of the analysis are highly sensitive to points from these three relatively weak areas but that this only has significant effects on conclusions for a system employing very high levels of acceleration. A hypothetical system with the same sensing capabilities and brake timings as the prototype system but where peak acceleration is capped to between 5 and 7 m/s^2 is much less sensitive to variations in the data.

TfLs mayoral targets for casualty reduction are expressed in terms of KSI casualties. That is, the targets are aimed at reducing the frequency or consequences of severe collisions, not minor collisions. TfL has also expressed an ambition to generate a business case such that it selects measures which helps achieve their casualty reduction targets but also helps operators in terms of reducing the cost of higher frequency but lower severity incidents. The predicted net effects of AEB can be considered against those targets separately.

Based on taking the central values in the range covered in the core analysis, the effect of each AEB system on fatalities can be seen in Figure 36, below.

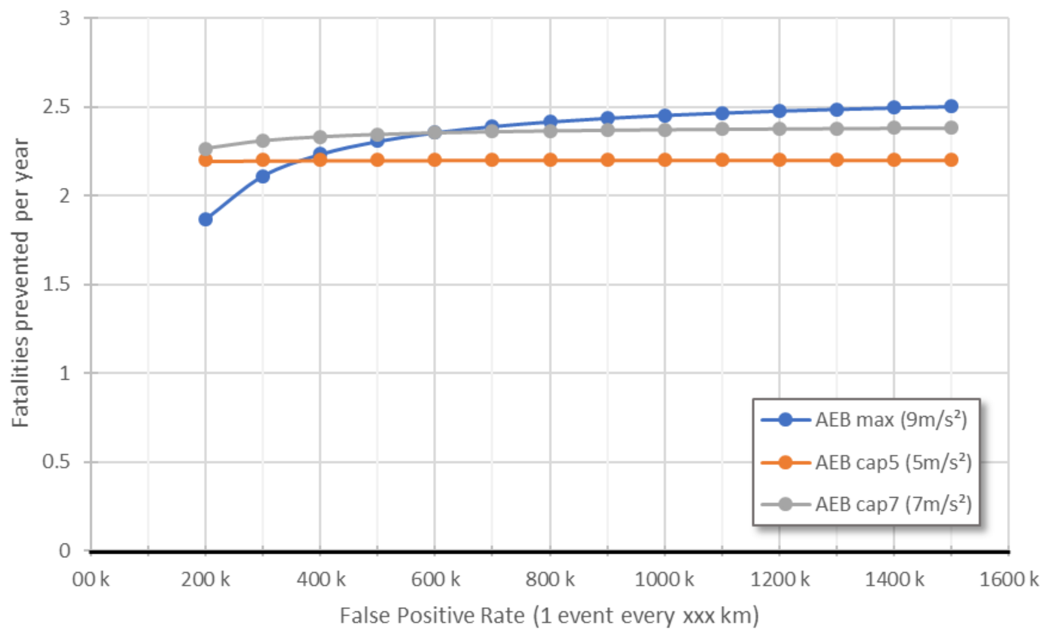


Figure 36: Central prediction (core analysis) of AEB effect on fatalities by false positive rate

For fatalities, a system that peaks at 9 m/s^2 (AEB$_{max}$) is forecast to be best once the false positive rate exceeds 600,000km (i.e. the vehicle must travel at least 600,000km between false positive activations). At higher false positive rates, a system with a maximum 7 m/s^2 is the best.

When serious injuries are considered, the AEB system with a lower cap on peak acceleration (AEB$_{cap5}$) is best, though the difference with the 7 m/s^2 system is small except at very poor false positive rates. The AEB system providing maximum deceleration (AEB$_{max}$) provides the lowest casualty savings but does still provide a net benefit once the low false positive rate of 300,000km is exceeded. This is shown in Figure 37.

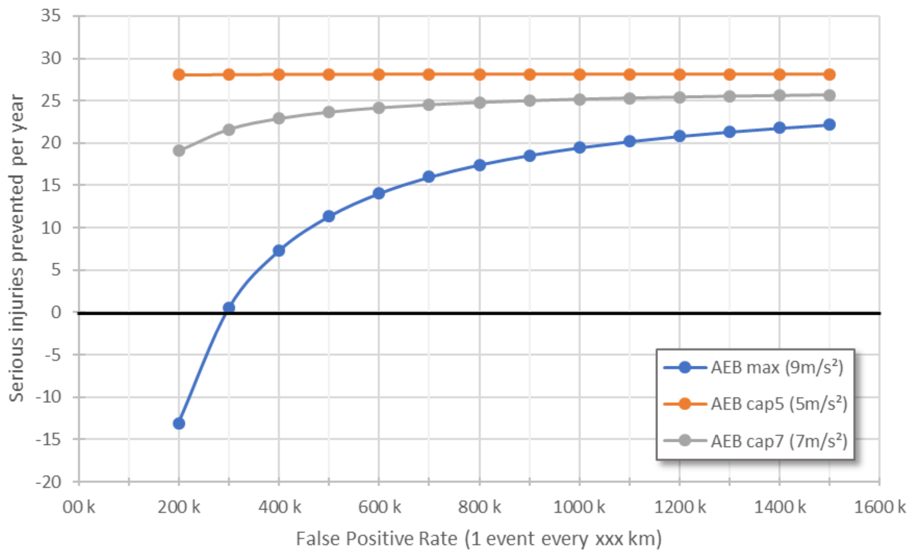


Figure 37: Central prediction (core analysis) of AEB effect on serious injuries by false positive rate

When all severities of injury are considered, the results are as shown in Figure 38, below.

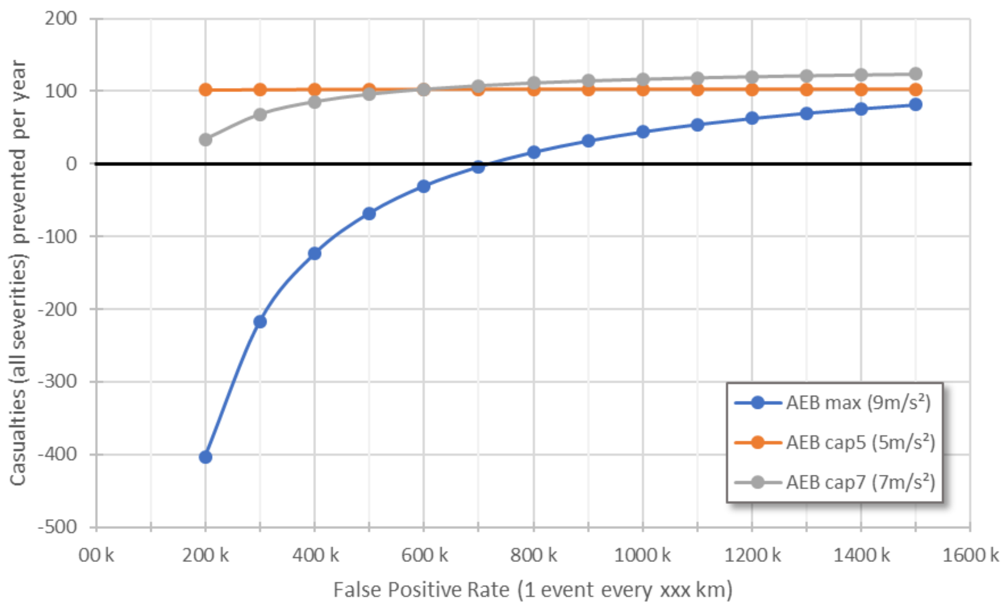


Figure 38: Central prediction (core analysis) of AEB effect on casualties of all severities by false positive rate

This suggests that for false positive rates greater than 700,000km, all the AEB braking strategies considered offer a net benefit in terms of the total number of casualties prevented.

If these benefits are monetised, the results are as shown previously in Figure 34, where the AEB system limited to a maximum deceleration of 5m/s² (AEB_{cap5}) appeared best but there was an overall benefit to all the braking strategies considered when false positive rates were good.

A range of possible options for implementation do, therefore, exist. The core analysis reported above illustrates that permitting an AEB system that maximises the braking performance of the bus (AEB_{max}) has the potential to save the most fatalities and is nearly as good, in terms of monetised casualty benefits, as the systems with a capped level of deceleration (AEB_{cap5} and AEB_{cap7}) provided a false positive rate in excess of one event every 800,000km is achieved. It is important to recognise that there are uncertainties in the analysis that could mean that the magnitude of benefits for the AEB_{max} system are lower than the central prediction, but equally the uncertainties could mean that it offers additional benefit. It is also worth noting that the test protocol would not *require* a system to produce maximum levels of deceleration, it will simply permit such systems to exist should the Original Equipment Manufacturers (OEMs) and tier-1 suppliers decide that this approach best suits their performance targets.

Regardless of the braking strategy adopted, if an AEB system is implemented, false positive events will occur, and these will create liability issues. In the current situation when a driver brakes to avoid a pedestrian, it is usually because the pedestrian has stepped into the path of the bus at a time when the bus driver cannot avoid collision. In this case, the driver and bus company will not generally be considered liable for causing the collision and, subject to legal interpretation, this will be at least a very strong factor mitigating against liability for any injuries that occur on the bus. When an AEB system applies the brakes, there will at least be questions over liability; did it need to brake as hard as it did? Did it brake harder than a driver would have? etc. There will be cases where there is debate as to whether it was a false positive event and where it is concluded to be a false positive there will be clear liability for the bus operator for any injuries caused. Ultimately, liability for these cases is likely to rest with the manufacturer and their supply chain but in the first instance a claim is likely to be made against the bus operator who would have the option to recover costs from the manufacturer under existing product liability laws. However, the operator may choose not to pursue such claims in low value cases because each case would need to be proved individually and, if the claim is defended by the manufacturer, the costs of the claim might exceed the amount recovered.

This problem cannot be avoided. However, the risks can be mitigated, and the process made as smooth as possible. A requirement for the bus to provide the facility for the operator to record relevant data every time the AEB system activated would be a key enabler of mitigation measures. If this were linked in to existing CCTV systems with recordings of acceleration, then for every incident in which the AEB activated there would be clear evidence of the external traffic situation, driver reactions and what the system did: when it warned, when it activated brakes, what level of deceleration was demanded, whether that exceeded driver demanded acceleration or not. This would help to ensure that any claims in genuine false positive incidents could be quickly paid with minimum legal cost and, where appropriate, cases where the system acted properly, could be disputed with a higher chance of success.

The analysis so far leaves considerable uncertainty around the conclusions because of limitations in the available data. This is particularly relevant for systems that maximise the potential benefits to collision partners, who are those most often killed.

The inclusion of requirements for data recording above would also enable the introduction of AEB on a controlled trial basis whereby a system could be introduced on a significant scale but with requirements for reporting of the data above and any injuries arising to TfL. If it was introduced in a way that allowed controlled comparison (e.g. 50% of vehicles used on a route, across several routes) then it would be possible to monitor the actual false positive rate in service, the actual frequency of driver demanded brake applications of different severities and the number of injuries arising from those events. This would allow a repeat of the benefit to cost analysis here, may provide data on which to base any changes to the maximum permitted levels of deceleration in a later phase, and/or to catch any adverse effects from false positives as early as possible.

A final benefit of allowing the data recording would be that the manufacturer could be sent a CCTV report for every false positive incident, allowing a valuable learning tool and helping to improve future generations of the system.

9 Cost-benefit analysis

The analysis of AEB systems was structured according to the definitions of true and false positive and negative activations as presented in section 8.

The analysis was based on consideration of three different concepts for the tuning of an AEB as defined in section 8.1.1: AEB_{max}, AEB_{cap5}, and AEB_{cap7}. Further information on the general approach adopted by the cost-benefit analysis may be found in Appendix B.

9.1 Target population

The annual target population in 2018 estimated for all outcome severities (fatal, serious and slight casualties) relevant to the AEB safety measure are presented in Table 29 below.

Target populations were calculated for bus occupants, VRUs (pedestrian and cyclists) and other vehicle occupants involved in collisions with a bus. All data was extracted from the UK STATS19 road safety database. For bus occupants at risk of injury from true positive and false positive incidents, target populations were calculated based on the DfT's published statistics on the number of passenger journeys on local bus services in London[7].

The incident types selected were based on the collision scenarios in which AEB is expected to be effective, i.e. bus-front to car/bus-rear, bus-front to crossing pedestrian, etc. Further detail on these scenarios is provided in section 8.

[7] Table BUS0103. Passenger journeys on local bus services by metropolitan area status and country: Great Britain, annual from 1970

Table 29: Estimated average annual target population in 2018 for all AEB safety measure solutions

Casualty Type	VRU and Other Vehicle Occupants			Bus Occupants		
	Fatal Casualties	Serious Casualties	Slight Casualties	Fatal Casualties	Serious Casualties	Slight Casualties
Pedestrians	4.2	35.7	101.0	0.0	0.0	2301.1
Cyclists	0.0	0.6	7.0	0.0	0.0	125.7
Car Occupants	0.0	1.2	41.6	0.0	0.7	18.9
Bus Occupants	0.0	0.9	19.6	-	-	-
Totals	4.2	38.4	169.2	0.0	0.7	2445.7
Calculated from UK STATS19 road safety database						
False Positives				2.2M	156.9M	2,122.4M
Calculated from passenger journeys on local bus services (DfT Bus Statistics Table BUS0103)						

9.2 Estimates of effectiveness

The true positive effectiveness of each AEB system was assessed using a case by case review of a sample of London fatalities completed in the first phase of this research and a sample of lower severity incidents obtained from a review of bus operator CCTV records. In each case, calculations and engineering judgments were made as to whether the AEB system was likely to have avoided the collision, reduced the impact speed or whether in fact it would have been unable to help in the given circumstances. The estimated effect identified in those samples was applied to a similar data set from STATS19 to estimate the casualty savings that could be expected within London each year (see section 8.2 for further details of the analysis).

The range of casualties that could be prevented or mitigated using this approach are displayed in Table 30. The effectiveness estimates for false positive rates look very low because they are calculated in relation to the number of passenger journeys completed each year in London (22 billion) rather than the number of road traffic collisions that occur. Section 8.3 describes the approach used for the false positive analysis.

Table 30: Estimated overall casualties prevented and mitigated effectiveness ranges for the AEB safety measure solution

Safety Measure Solution	Casualty Type	Casualties Prevented			Casualties Mitigated	
		Fatal Casualties	Serious Casualties	Slight Casualties	Fatal to Serious	Serious to Slight
AEB_{max}	Pedestrians	48%	85-89%	85-89%	14%	4-7%
	Cyclists	0%	75%	75%	0%	0%
	Car Occupants	0%	43-50%	43-50%	0%	0%
	Bus Occupants (v Bus)	0%	43-50%	43-50%	0%	0%
	Bus Occupants (v Ped)	0%	0%	0.26-1.14%	0%	0%
	Bus Occupants (v Cyclist)	0%	0%	0.2-1.0%	0%	0%
	Bus Occupants (v Car)	0%	43-50%	43-50%	0%	0%
	Bus Occupants (False +)	5.3×10^{-9}-2.2×10^{-5}%	4.1×10^{-9}-1.7×10^{-5}%	3.9×10^{-9}-1.6×10^{-5}%	0%	0%
AEB_{cap5}	Pedestrians	10%-24%	48-74%	48-74%	29-43%	15-41%
	Cyclists	0%	50-75%	50-75%	0%	0-25%
	Car Occupants	0%	14-29%	14-29%	0%	14-29%
	Bus Occupants (v Bus)	0%	14-29%	14-29%	0%	0%
	Bus Occupants (v Ped)	0%	0%	0.3-0.6%	0%	0%
	Bus Occupants (v Cyclist)	0%	0%	0.23-0.55%	0%	0%
	Bus Occupants (v Car)	0%	14-29%	14-29%	0%	0%
	Bus Occupants (False +)	1.4×10^{-9}-2.3×10^{-9}%	1.1×10^{-9}-1.8×10^{-9}%	1.0×10^{-9}-1.7×10^{-9}%	0%	0%
AEB_{cap7}	Pedestrians	29%-38%	78-81%	78-81%	19-29%	7-11%
	Cyclists	0%	50-75%	50-75%	0%	0-25%
	Car Occupants	0%	36%	36%	0%	7-14%
	Bus Occupants (v Bus)	0%	36%	36%	0%	0%
	Bus Occupants (v Ped)	0%	0%	0.3-1.1%	0%	0%
	Bus Occupants (v Cyclist)	0%	0%	0.2-1.0%	0%	0%
	Bus Occupants (v Car)	0%	36%	36%	0%	0%
	Bus Occupants (False +)	5.2×10^{-9}-2.0×10^{-6}%	4.1×10^{-9}-1.6×10^{-6}%	3.9×10^{-9}-1.5×10^{-6}%	0%	0%

9.3 Fleet fitment and implementation timescales

Timescales were determined for each AEB solution to develop a roadmap for fleet fitment and policy implementation (Table 31). The timescales were determined based on stakeholder consultations with bus manufacturers for first-to-market timescales and TfL for proposed timescales for policy implementation. Bus operators and tier 1 suppliers contributed to establishing the estimates for current levels of fleet fitment and expected years to full fleet fitment after implementation. Suppliers agreed that retrofit solutions were not technically feasible and that it was technically feasible to produce a system capable of detecting all relevant target populations in the proposed timeframes (cars, pedestrians and cyclists). Please see the associated stakeholder consultation report for further information on stakeholder feedback on fleet fitment and policy implementation timescales.

Table 31: Implementation timescales for AEB safety measure solution

Safety Measure Solution	First-to-Market	Date Policy Implemented	Current Fleet Fitment	Full Fleet Adoption (yrs)	
				Retrofit	New Build
AEB_{max}	2020	2024	0%	-	12
AEB_{cap5}	2020	2024	0%	-	12
AEB_{cap7}	2020	2024	0%	-	12

9.4 Casualty benefits

Table 32 below summarises the estimated total change in the number of casualties expected in London during the period 2019-2031 for the three different AEB tuning concepts considered. Outcomes have been monetised to estimate the total value of these casualty reductions to society.

Table 32: Estimated total change in number and total value (NPV) of casualties over the 12-year analysis period (2019-2031) for the AEB safety measure solutions (casualty and cost increases are shown in parentheses)

Safety Measure Solution	Casualty Type	Number of Casualties (n)			Total Value (NPV) of Casualties (£M)
		Fatal Casualties	Serious Casualties	Slight Casualties	
AEB$_{max}$	Pedestrians	12.3-12.3	153-153	393-417	60.3-60.7
	Cyclists	0	2.9-2.9	34-34	1.1-1.1
	Car Occupants	0	2.3-2.7	80-93	1.7-2.0
	Bus Occupants (v Bus)	0	1.8-2.1	39-46	1.0-1.2
	Bus Occupants (v Ped)	0	0	(126)-(28)	(2.0)-(0.4)
	Bus Occupants (v Cyclist)	0	0	(5)-(1)	(0.1)-(0.0)
	Bus Occupants (v Car)	0	1.4-1.6	38-44	0.9-1.0
	Bus Occupants (False +)	(2.2)-0	(124)-0	(1,578)-0	(54.8)-0.0
	Totals	10.0-12.3	37-162	(1125)-606	8.2-65.6
AEB$_{cap5}$	Pedestrians	10.4-10.4	141-144	161-328	50.7-54.0
	Cyclists	0	2.9-2.9	22-34	0.9-1.1
	Car Occupants	0	2.3-2.3	25-53	0.9-1.3
	Bus Occupants (v Bus)	0	1.8-1.8	12-26	0.5-0.8
	Bus Occupants (v Ped)	0	0	(58)-(15)	0.2-0.9
	Bus Occupants (v Cyclist)	0	0	(3)-0	0.0-0.0
	Bus Occupants (v Car)	0	1.4-1.4	12-25	0.5-0.7
	Bus Occupants (False +)	0	0	0	0.0-0.0
	Totals	10.4-10.4	150-152	170-449	52.6-57.6
AEB$_{cap7}$	Pedestrians	11.3-11.3	144-146	352-376	56.1-56.8
	Cyclists	0	2.9-2.9	22-34	0.9-1.1
	Car Occupants	0	2.3-2.7	66-66	1.5-1.6
	Bus Occupants (v Bus)	0	1.8-2.1	33-33	0.9-0.9
	Bus Occupants (v Ped)	0	0	(113)-(24)	(1.8)-(0.4)
	Bus Occupants (v Cyclist)	0	0	(5)-(1)	(0.1)-(0.0)
	Bus Occupants (v Car)	0	1.4-1.6	31-31	0.8-0.8
	Bus Occupants (False +)	(0.2)-0	(11.8)-0	(150)-0	(5.2)-0.0
	Totals	11.1-11.3	141-155	235-514	53.1-60.9

9.5 Cost implications

The costs of AEB requirements as part of the BSS can be divided into four 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

Based on stakeholder feedback, baseline costs associated with developing, manufacturing and gaining approval for the fitment of AEB on buses was estimated to be £2,000-4,000/vehicle. It was considered that these costs would apply to all the AEB tuning concepts analysed in this project.

Bus operators expected that normal bus training should be sufficient to cover any driver training required and as such it was estimated that there would be no implementation costs to the operators.

Although AEB systems require only minimal maintenance, it may be necessary to recalibrate the system if sensors have been damaged as part of a collision or if a windscreen needs replacing. It was estimated that a baseline cost of £400-600 per bus would account for such cases across the lifetime of the vehicle.

The annual change to the number of incidents has been used to estimate the changes in insurance claims costs that may be expected by regulating the performance of buses for each AEB tuning concept. Changes in the costs of insurance claims are highlighted below in Table 33.

Table 33: Estimated changes in costs per bus (NPV) and total fleet costs (NPV) over the 12-year analysis period (2019-2031) for the AEB safety measure solution (cost reductions are shown in parentheses)

Safety Measure Solution	Cost Description	Cost (NPV) Per Bus (£)	Total Cost (NPV) (£M)
AEB_{max}	Change in Technology Costs	1,866-3,732	14.9-29.9
	Change in Implementation Costs	0	0
	Change in Operational Costs	176-265	1.4-2.1
	Change in Insurance Claims Costs	(402)-929	(3.2)-7.4
	Totals	**1,114-4,399**	**8.9-35.2**
AEB_{cap5}	Change in Technology Costs	1,866-3,732	14.9-29.9
	Change in Implementation Costs	0	0
	Change in Operational Costs	176-265	1.4-2.1
	Change in Insurance Claims Costs	513-795	4.1-6.4
	Totals	**1,247-3,484**	**10.0-27.9**
AEB_{cap7}	Change in Technology Costs	1,866-3,732	14.9-29.9
	Change in Implementation Costs	0	0
	Change in Operational Costs	176-265	1.4-2.1
	Change in Insurance Claims Costs	519-846	4.2-6.8
	Totals	**1,197-3,478**	**9.6-27.8**

9.6 Benefit-cost analysis outcomes

Table 34 provides estimates for the break-even costs, discounted payback period and benefit-cost ratios associated with the different AEB tuning concepts considered in this analysis. Positive benefit-cost ratios are highlighted in **green**, whilst marginal benefit-cost ratios are highlighted in **orange**.

Table 34: Estimated 12-year analysis period (2019-2031) break-even costs per vehicle (NPV), discounted payback periods and benefit-cost ratios (NPV) for the AEB safety measure solution

Safety Measure Solution	Break-Even Costs (NPV) (£)	Discounted Payback Period	Benefit-Cost (NPV) Ratio
AEB_{max}	1,028-8,203	2021-2031+	**0.23 - 7.36**
AEB_{cap5}	6,574-7,203	2022-2026	**1.89 - 5.77**
AEB_{cap7}	6,640-7,618	2021-2026	**1.91 - 6.37**

10 Conclusions and next steps

The evaluation of AEB has found that:

- Strong potential benefits exist in true positive situations, in particular for preventing pedestrian fatalities. Up to around 25% of pedestrian fatalities caused in collisions with a bus could be prevented.
- In addition to this, there are significant benefits in reducing more minor collisions with other vehicles, particularly cars and buses. This will have little effect on fatality statistics but should benefit bus operators in terms of reducing high frequency damage and low severity injury claims, reducing operating costs and downtime.
- The risk to occupants in true positive situations exists but is relatively low due to low numbers of true positive events, potentially earlier brake intervention allowing lower peak decelerations and only small increases in required decelerations compared to those recorded in situations where the driver applied the brakes (on the assumption that this occurs in true positive situations).
- The risk to occupants in false positive events is significant and a low false positive rate is very important to minimise this risk.
- Permitting an AEB system that maximises the braking performance of the bus (AEB_{max}) has the potential to save the most fatalities, provided that false activations occur less than once every 600,000 vehicle km on average.
- Capping peak deceleration to a maximum of 7 m/s^2 has the potential for the largest reduction in monetised casualty benefit. This is because the analysis shows that the reduced deceleration substantially reduces the risk of large numbers of slight injuries to bus occupants as a consequence of false positive activation, whilst still achieving most of the monetised benefits for fatalities.
- However, this analysis will only hold true if the correlation between the risk of injuries to standing and seated (but unrestrained) occupants is with peak deceleration only. Experimental data suggests that the rate of change of deceleration (brake jerk) is also an important factor in the risk of injury but the empirical analysis could not account for this factor. For a capped deceleration there would be an incentive to increase the brake jerk to improve true positive performance. Thus, there is a risk that capping deceleration could fail to achieve the benefits expected by the analysis, or even reverse them.
- Thus, provided a false positive rate of less than one activation every 600,000 km is achieved, then a substantial net monetised benefit is expected from AEB. If TfL choose to implement a requirement for AEB they will have options for implementation:
  - Prioritise fatality reduction – allow maximum braking to be used, which risks increases in less severe injuries to bus occupants

    - Prioritise avoidance of new risks – cap deceleration, which may reduce the new risks to bus occupants, depending on the real-world effect of brake jerk, but will reduce the achievable effect on fatalities.

- If AEB were to be introduced, requiring that the bus enables data to be independently captured in defined CCTV/telematics systems would be very beneficial: enabling more efficient claims management, introduction of AEB in a large-scale controlled trial and feedback to manufacturers for continuous improvement.
- The analysis of benefits versus disbenefits is strongly dependent on two key input parameters that are weakly evidenced: the frequency with which heavy brake applications ($5m/s^2$+) occur in real service and the frequency with which bus occupant casualties occur under different levels of braking acceleration. This is particularly true when considering an AEB system that can apply peak braking of 9 m/s^2. If TfL wish to increase confidence in these areas this could be achieved with a much larger study of bus occupant injuries under braking using CCTV and telematics (acceleration) data and a larger road trial documenting the frequency of different acceleration levels of buses in normal service.
- Requirements have been developed for AEB that effectively define a minimum standard that must be achieved in terms of true and false positive performance in order to be considered an AEB system suitable for a London bus. In addition to this, the tests then measure and rate additional performance in excess of this standard. Thus, the market is free to choose how to implement AEB in terms of deceleration levels, brake jerk etc., within the limit of 7 m/s^2 if TfL choose to implement that option.
- These are track test assessments that ensure to the extent possible that the systems are well designed and will work in the real world. However, there are an almost infinite range of circumstances that can be encountered in the real world and not all can be tested on a test track. It is, therefore, very important that industry design for real world use and not just test track performance. This is of concern in relation to false activations. The inclusion of a requirement for industry to demonstrate to TfL how they have satisfied themselves that they will achieve a defined false positive rate in the real world, would add additional reassurance of proper design diligence.

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.

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Appendix A Analysis to support route selection for the AEB road trial

A.1 Introduction

The routes selected considered the wide range of bus driving environments likely to be encountered in service in London, whilst still being broadly representative of the most common routes and situations. Pedestrian collisions are the most frequent fatal collision type of relevance and situations with crowds of pedestrians are cited as difficult situations for AEB routes with a higher risk of such incidents have been included. Also, consideration was given to the occurrence of bus occupant injuries in incidents without a collision since these represent a potential disbenefit to AEB if the system delivers high levels of deceleration. To ensure that the overall test program was representative of the varied routes experienced in London, a route considered to have a lower risk of pedestrian casualties was selected.

Running the test programme required the support of bus operators and so the practicalities of running specific routes and/or the use of depot facilities was also factored into the final route selection.

A.2 Analysis of incident and exposure data

Data from the IRIS database (2014/15, 2015,16 and 2016/17) was combined with data on TfL bus usage and kms driven from the same years and analysed by bus route to identify some high and low risk bus routes in terms of causing pedestrian and/or bus occupant casualties.

A.2.1 Pedestrian casualty risk

The data was ranked by the pedestrian casualty rate: that is, the number of pedestrian casualties on a given route per million bus km on that route. The data was cross checked against the top 10 when only the absolute number of casualties was considered. The top 10 routes that appeared in both lists are shown in Table 35.

Table 35: Pedestrian casualties, bus km, and pedestrian casualty rate by London bus route, ranked by highest casualty rate and absolute number of casualties. Source: IRIS and bus usage statistics for period 2014/15, 2015/16 and 2016/17)

Route #	Number of pedestrian casualties	Bus km	Pedestrian casualties per million bus km
75	9	2,764,664	3.3
55	15	4,651,300	3.2
98	9	3,067,398	2.9
133	11	3,858,052	2.9
73	19	6,675,443	2.8
35	8	3,042,708	2.6
137	11	4,226,621	2.6
391	8	3,078,144	2.6
220	8	3,333,669	2.4
281	11	4,717,362	2.3

The routes with the lowest risk of pedestrian casualties, where at least one casualty had occurred[8], are shown in Table 36. The casualty risk and bus km travelled are all broadly similar across these routes.

Table 36: Pedestrian casualties, bus km, and pedestrian casualty rate by London bus route, ranked by lowest casualty rate and absolute number of casualties. Source: IRIS and bus usage statistics for period 2014/15, 2015/16 and 2016/17)

Route #	Number of pedestrian casualties	Bus km	Pedestrian casualties per million bus km
94	1	4,122,610	0.2
266	1	4,209,152	0.2
51	1	4,331,496	0.2
285	1	4,355,965	0.2
114	1	4,370,182	0.2
174	1	4,476,465	0.2
358	1	4,655,220	0.2
12	1	5,128,508	0.2
5	1	5,610,067	0.2
140	1	6,750,964	0.1

[8] In order to be recorded on the IRIS database with pedestrian casualty selected, at least one incident must have occurred. Routes with a similar distance travelled that suffered zero pedestrian casualties may in fact be lower risk, though they may also be not statistically significantly different (i.e. 1 casualty or none could largely be related to chance).

A.2.2 Bus occupant casualty risk

IRIS data for slip, trip and fall (STF) incidents were analysed and ranked by the bus occupant casualty rate; that is, the number of bus occupant injuries on a given route per million bus km on that route, for incidents that did not involve a collision but where the injuries were deemed to have been caused by braking. The data was cross checked against the top 10 when only the absolute number of casualties was considered. The top 10 routes that appeared in both lists are shown in Table 37, below.

Table 37: Bus occupant casualties, bus km, and bus occupant casualty rate by London bus route, ranked by highest casualty rate and absolute number of casualties. Source: IRIS and bus usage statistics for period 2014/15, 2015/16 and 2016/17)

Route #	Number of bus occupant casualties	Bus km	Bus occupant casualties per million bus km
88	150	3,284,868	45.7
432	45	1,592,958	28.2
144	79	2,986,068	26.5
67	54	2,531,399	21.3
149	96	5,125,847	18.7
297	60	3,299,402	18.2
50	42	2,568,002	16.4
175	41	2,540,202	16.1
75	41	2,764,664	14.8
11	41	2,959,675	13.9

The only route to appear in the top 10 for bus occupant casualties and the top 10 for pedestrian casualties in #75. The routes with the lowest risk of bus occupant casualties, where at least one casualty had occurred, are shown in Table 38.

Table 38: Pedestrian casualties, bus km, and pedestrian casualty rate by London bus route, ranked by lowest casualty rate and absolute number of casualties. Source: IRIS and bus usage statistics for period 2014/15, 2015/16 and 2016/17)

Route #	Number of bus occupant casualties	Bus km	Bus occupant casualties per million bus km
381	1	3,170,332	0.3
99	1	3,387,360	0.3
81	1	3,456,736	0.3
28	1	3,589,125	0.3
W15	1	3,731,932	0.3
266	1	4,209,152	0.2
345	1	4,238,948	0.2
114	1	4,370,182	0.2
134	1	4,713,142	0.2
472	1	5,095,625	0.2

A.3 Route selection

This section provides a brief explanation for the chosen routes:

Route #75 – This route appears in the Top 10 risk routes for both pedestrian and bus occupant casualties.

Route #55 – This route has the second highest pedestrian casualty risk after route #75.

Route #149 – One of the bus operators that offered support for this trial specified that they would be able to provide a driver from their North London depot. Route #149 is the route with the highest pedestrian risk from that depot.

Route #174 – This route represents a lower risk for pedestrian casualties and is one of the lowest ranked routes that is operated by one of the bus operators that has offered support for this trial.

Route #159 – Chosen because the bus manufacturer producing the prototype system has undertaken preliminary testing on bus route 159, which is also used as the basis for a standardised emissions test cycle. The route does not appear in any of the top or bottom ten risk routes.

These five routes are shown below in Figure 39 to Figure 43 with information from the TfL website on the off-peak duration of each.

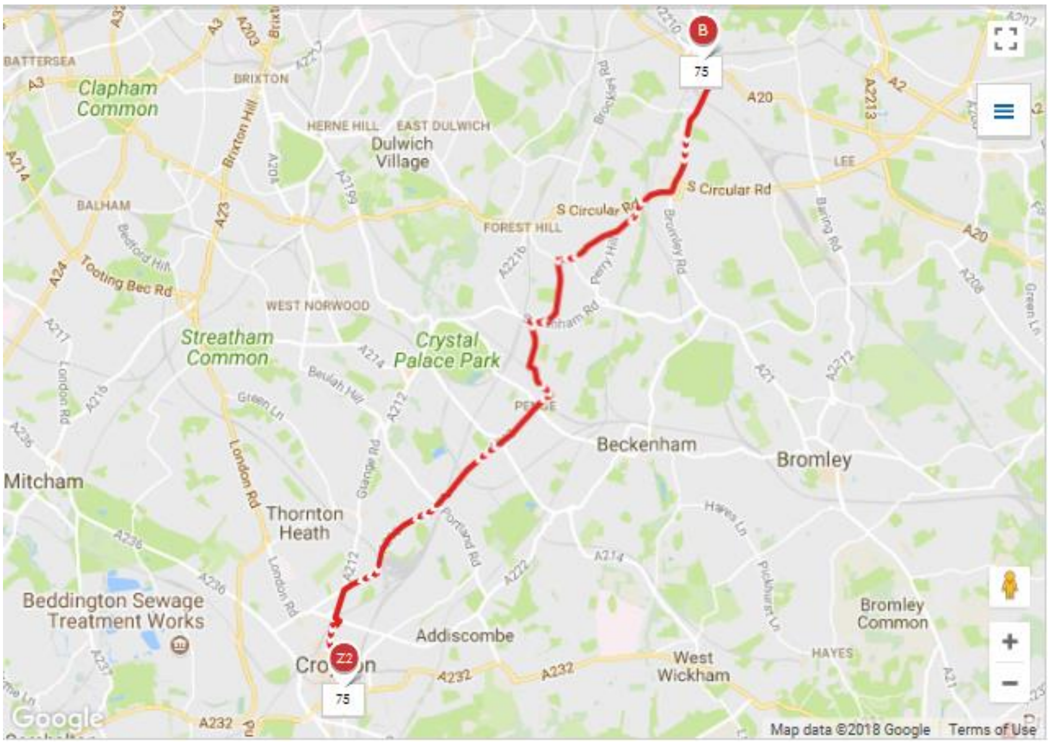

Figure 39: Route #75; off-peak duration 57 mins

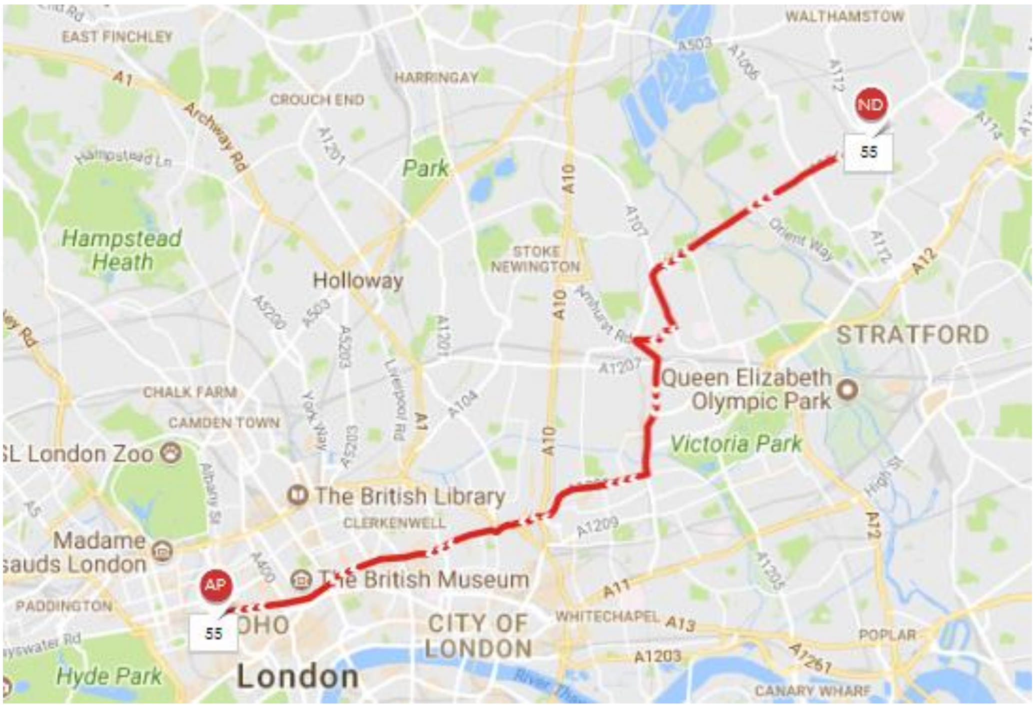

Figure 40: Route 55; off-peak duration 77 mins

Figure 41: Route 149; off-peak duration 76 mins

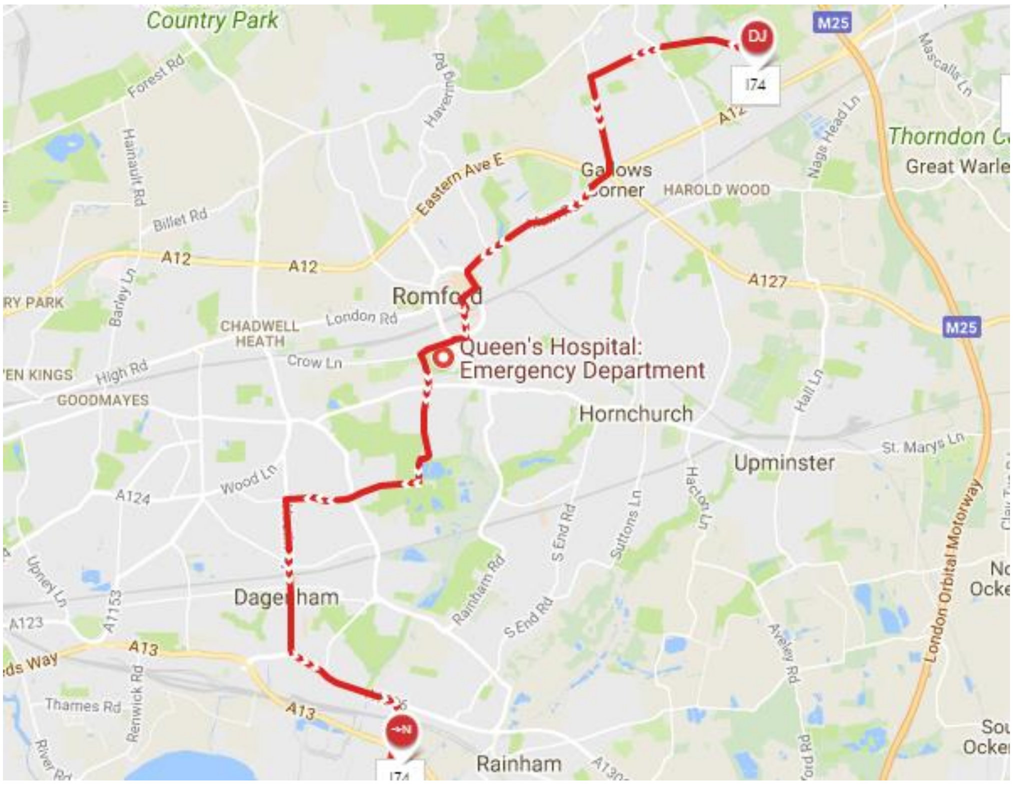

Figure 42: Route 174; off-peak duration 55 mins

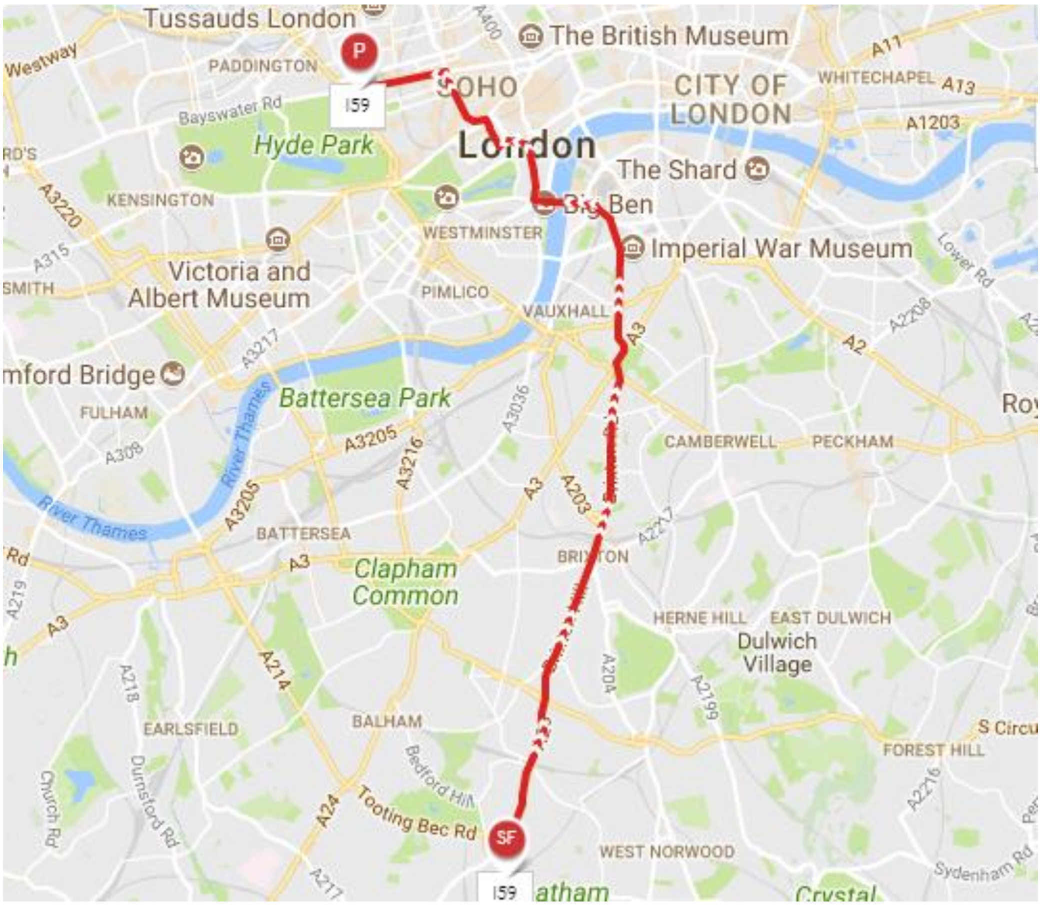

Figure 43: Route 159; off-peak duration 65 mins

Appendix B 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, several key CBA outcomes can be determined for each safety measure solution. These outcomes include values for the target populations, effectiveness, fleet fitment timeframes, casualty reduction benefits, costs per vehicle, total fleet costs, monetised casualty benefits, break-even costs and benefit-cost ratios associated with each solution. The theory behind calculating these values is covered in the following paragraphs.

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

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

(Equation 1)

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

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

(Equation 2)

Fleet fitment and implementation timescales were determined for each safety measure solution based on a stakeholder consultation with the bus industry. This was used to include the temporal aspects of the penetration of each safety measure solution in to the TfL fleet, which can then be used for better determining the changes in costs and benefits over time. The ‘first-to-market’ timescales were established based on bus manufacturer feedback and represent the earliest point in time that the leading manufacturer will be able to bring the particular solution to market. The timescales for ‘policy implementation’ were proposed by TfL based on bus manufacturer feedback on when series production would be possible for at least three different manufacturers. Current levels of fleet fitment for each solution were established based on bus operator feedback, whilst the estimated period of time that it would take to fit the entire TfL fleet with the solution was determined for new build buses (12 years), solutions fitted during refurbishment (7 years) and retrofit solutions (timeframes based on supplier feedback). This gave a year-on-year fleet penetration value, based on the proportion of the fleet fitted with the particular solution, for each solution and each year of the analysis period.

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

$$Casualty\ Reduction\ = Target\ Population \times Overall\ Effectiveness \times Fleet\ Penetration$$
(Equation 3)

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

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

Claims costs reductions for each year of the analysis period were calculated by combining average insurance claim costs (calculated from operator provided data), with the expected annual changes in incidents for each outcome severity (Equation 4). For the purposes of this report, claims reductions for fatalities was assigned a range of £25,000-45,000, seriously injured casualties assigned a range of £35,000-75,000, slightly injured casualties assigned a range of £4,500-8,500, major damage-only collisions assigned a range of £3,000-6,000 and minor damage-only collisions assigned a range of £200-2,000.

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 NPV of the costs per vehicle were then calculated by dividing the total costs by the total number of fitted vehicles in the fleet. A discounting factor of 3.5% and interest rates that reflect forecasted annual changes in RPI were again applied.

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

(Equation 4)

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

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

(Equation 5)

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

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

(Equation 6)

Finally, the Discounted Payback Period (DPP) was established based on calculations for the benefit-cost ratio ranges for each year of the analysis period. To establish the DPP range, the year where each boundary of the benefit-cost ratio first exceeded the value of one was calculated. This gives a range for the expected period 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: Advanced Emergency Braking (AEB)

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.

Advanced Emergency Braking (AEB) is also called Automated or Autonomous Emergency Braking, but these names generally refer to the same system. It can be described as a Driver Assist system, designed to help the driver to avoid or mitigate the severity of incidents.

An AEB system uses forward looking sensors such as Lidar, Radar, Camera, or fusions of data from more than one sensor, to identify a risk of an imminent collision. It will typically first warn the driver of the risk and, if the driver does not act, then it will apply braking automatically to avoid the collision or to reduce the collision speed and therefore the potential for injury. It will warn and intervene in an emergency in the last few seconds before an impact and provides braking much later than during normal driving. Systems will be available that respond in front-to-rear collisions with other vehicles and frontal collisions with pedestrians crossing the road, or cyclists travelling more slowly ahead of the bus.

AEB standards have previously been developed for HGVs and cars, but buses pose a unique additional challenge because of the multiple passengers that are seated and unbelted, or who might be standing. AEB has been proven effective in other vehicle types, in both front-to-rear vehicle collisions and pedestrian collisions. Analysis strongly suggests it will provide considerable benefit when fitted to buses too. However, on very rare occasions, an AEB system can activate when it did not need to (a false positive) because it incorrectly identified a collision threat. For all vehicle types this creates a risk of unnecessary collisions with following vehicles, but for a bus, each false activation also carries a risk that it could cause passenger injury.

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

TRL
Crowthorne House, Nine Mile Ride,
Wokingham, Berkshire, RG40 3GA,
United Kingdom
T: +44 (0) 1344 773131
F: +44 (0) 1344 770356
E: enquiries@trl.co.uk
W: www.trl.co.uk

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