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Bus Safety Standard: Bus Braking Data Analysis

Martin Dodd, Iain Knight, Alix Edwards, Mervyn Edwards, Peter Ball, Josh Appleby, Jack Radcliffe

Report details

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Executive Summary

The mayor of London has adopted a ‘Vision Zero’ approach to road safety. The main objectives are that:

- nobody should be killed on or by a London bus by 2030,
- nobody should be killed or seriously injured (on, or by any road vehicle) by 2041.

Advanced Emergency Braking (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. If the driver has not acted to prevent a detected collision, then the brakes are automatically applied to slow, or ideally stop, the vehicle before impact. 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.

Prior research has identified that AEB is effective in preventing and mitigating vehicle and pedestrian collisions. It could be the single biggest bus vehicle technology contributor to achieving vision zero, with potential to prevent up to around 25% of pedestrian fatalities from collisions involving buses. Currently TfL’s Bus Safety Standard (BSS) requires the fitment of AEB to new buses from 2024 and has encouraged it since 2020.

Buses carry unrestrained and standing passengers, a minority of whom do already sustain (mainly minor) injuries due to manually applied braking. There are concerns that AEB could exacerbate this problem if it brakes when not necessary (referred to as false positives). A predictive model was developed to quantify the net effects, i.e. pedestrian casualties saved and bus occupant casualties caused. Results suggested that with good false positive rates the overall outcome could be beneficial, but potential weaknesses in the model were identified. These included the size of the naturalistic driving data sample to calculate the frequency of brake applications in service used to estimate the effect of false positives and the size of the CCTV incident data sample to calculate the relationship between the magnitude of brake applications and bus occupant injury.

This current study was commissioned and designed to eliminate these potential weak spots, correct the statistical weaknesses in the original predictive model and increase the robustness of the conclusions to allow better informed decisions on the implementation of AEB and the specifications required. Wherever possible, the other inputs used in the model have been kept the same as the previous model to ensure like is compared with like.

The sample size of naturalistic driving data was increased from 400 km to >1 million km in the core data set and >1 billion km including a supporting data set. CCTV incident data has almost quadrupled in size to 300 cases. The evidence base can now be considered very robust.

The new data predicts stronger net benefits with much less sensitivity to false positive rate than the prior study (Knight *et al.*, 2019). It suggests that AEB systems applying maximum braking will provide the best outcomes. However, it was confirmed that within this large net benefit across all casualty groups, the benefits for bus occupants specifically would be slightly outweighed by disbenefits.

Increased confidence in the robustness of the model predicting the effect, and the changes in the identification, magnitude and distribution of risks gave rise to the following potential policy options:

1. Do Nothing – low true positive performance, high false positive performance (including a requirement of no more than one false positive per 600,000 km travelled).
2. Decrease minimum average distance between false positives. Take the opportunity to reduce the stringency of false positive performance given the analysis now shows a considerably reduced risk of adverse consequences.
3. Set false positive rate in proportion to maximum deceleration. Allow an approach that flexes the standard required for false positives in relation to the likely consequences of false positives in terms of high deceleration braking.
4. Permit experience gained in other markets to be used as evidence of expected false positive rate in London. Reduce the burden on industry to prove they meet the requirement in London by allowing evidence of good performance in comparable cities to be used in approvals.
5. Increase true positive performance. The evidence now shows high deceleration strategies produce the strongest net benefit; this option will maximise the benefit.
6. Update the requirements over time via the BSS Roadmap. The requirements can be updated in phases set out in the roadmap, in order to deliver an increase in safety performance balanced with encouraging market entry for AEB on buses as a new technology.

Implementing option 5 alone (i.e., with Option 1) would represent the safest approach (high true and false positive performance) but would be most demanding for industry to meet. Combining option 5 with options 2 or 3 and/or option 4 would still maintain a high true positive performance but may slightly increase risks for bus occupants and may make it easier for some manufacturers to develop a product. Implementing option 2 or 3 in isolation would risk the market delivering cheap but ineffective systems.

In order to best inform the choice of option, it is recommended that TfL consult with industry to identify the likely responses to each different approach.

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1 Introduction

The mayor of London has adopted a 'Vision Zero' approach to road safety. The main objectives are that:

- nobody should be killed on or by a London bus by 2030;
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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.

Prior research (Edwards *et al.*, 2017) identified that fatalities from collisions involving buses are mainly pedestrians and that Advanced Emergency Braking (AEB) systems effective in reducing pedestrian collisions were available for cars. On this basis the idea to require the fitment of AEB systems to buses was born and incorporated into TfL's Bus Safety Standard (BSS). The research work to develop TfL's BSS found that AEB systems had the potential to prevent up to around 25% of pedestrian fatalities from collisions involving buses, which made it the single biggest potential contributor identified to enable the achievement of Vision Zero for buses. Currently TfL's BSS requires the fitment of AEB to new buses from 2024 and has encouraged it since 2020.

AEB on buses is a unique challenge because buses carry unrestrained and standing passengers, a substantial number of whom do already sustain (mainly minor) injuries from falls because of manually applied braking. If AEB brakes when not necessary, (referred to as false positives), this could increase bus passenger falls, thus reducing or even reversing the benefits of AEB. The original BSS research suggested a minimum average distance travelled between 'false positive' brake applications of 600,000 bus km should ensure strong net benefits. However, there were uncertainties in that analysis, and no strong evidence was available that this relatively low level of 'false positives' would be achievable on production type AEB systems for buses in a busy city like London.

The previous work was all undertaken before the COVID-19 pandemic. During the pandemic, London has seen substantial changes to bus traffic, bus occupancy and the number of people walking and cycling. These factors are all relevant when considering the net effect of AEB and need to be considered when assessing the effect of fitting AEB to buses in the future.

TfL commissioned TRL & Apollo Vehicle Safety to undertake detailed data collection and analysis of the braking characteristics of normal, human driven, buses in-service and to study incidents of passenger falls from CCTV. The aim of this was to greatly strengthen the original analyses with substantially increased sample sizes, to consider the potential effect of other braking characteristics such as speed and jerk, and to consider the boundaries of what effects Covid induced changes to bus travel might mean for the case for bus AEB.

The main aim of this project was to correct the statistical weaknesses in the original predictive model, and to assess whether this affected the case for or against AEB on buses. As such, in the core analyses, other variables have not been updated so as to avoid confusion with changes that have occurred due to other factors such as changes in the traffic levels, incident numbers etc are not taken into account. These changes have been accounted for separately in general consideration of post pandemic scenarios of future travel in London.

It is also important to note that this project considers bus braking data analysis and how that informs the implementation of AEB in isolation. It does not consider any other vehicle safety measures applied as part of the fuller Bus Safety Standard, nor any other pillars of TfL’s safe systems approach.

2 Defining the problem

2.1 Theory on passenger falls and relationship to characteristics of braking

The root of the problem under consideration in this project is the fact that a significant number of London bus passengers already record slip, trip or fall incidents under normal human braking. Clearly, concerns exist that AEB could exacerbate this.

There has been a significant quantity of experimental research on human balance and the ability to resist falls under acceleration, much in relation to train travel but also in relation to bus travel and other situations.

(De Graaf and Van Weperen, 1997) explored the limits of acceleration the human body could withstand without losing equilibrium. They tested 22 subjects from 26 to 63 years of age on a treadmill with a conveyor belt that was moved to subject the participants to forward, backward or sideways accelerations. The conveyor was initially accelerated linearly to a low speed over a distance of 10 cm. The test stimulus was then applied over a distance of 45 cm and then the belt was brought to a halt over 25 cm. Accelerations of between 0.3 and 1.6 m/s^2 were tested. The rate of change of acceleration from between 1.0 and 7.0 m/s^3. The participants were stood with their feet together and were not holding on. They found mean thresholds of acceleration where the participants were just about able to retain their balance without problems were between 0.45 and 0.6 m/s^2, depending on the direction faced (forward, sideways, backward).

These thresholds were shown to be regularly exceeded in public transport operations, where a small sample of real-world measurements were taken and for a bus, a maximum longitudinal value of 2.15 m/s^2 was observed as well as a 4 m/s^2 maximum cornering acceleration. (De Graaf and Van Weperen, 1997) concluded that these real-world values would be “impossible to endure without support” and cited prior research to suggest that the use of handgrips would increase the ability of passengers to cope to a deceleration of 1.5 m/s^2.

To further investigate the influence of brake jerk, they repeated their original experiment with ten new participants, all accelerated at 1 m/s^2 but with brake jerk varying from 1 to 10 m/s^3. It was found that 65% of participants retained balance (without support) when jerk was 1.0 m/s^3, dropping to 2.5% at 10 m/s^3. As such, they concluded that prior research suggesting a brake jerk limit of around 0.6 m/s^3 was appropriate.

A similar methodology was used by (Sarraf, 2011) but with higher levels of peak acceleration (1 to 2 m/s^2) and an objective to assess how participants reacted to maintain balance given different types of hand hold. This study noted that in both cases, the maximum speed was 0.8m/s and the maximum motion distance was 1.8m. Thus, the duration of the event would have been very short. Rate of change of acceleration was not reported but from graphs that were provided would have been in the region of 6 or 7 m/s^3.

(Kirchner *et al.*, 2014) noted that these “posturographic” laboratory studies cannot really be generalised and transferred to the perturbations experienced in real life buses, because in real life accelerations and decelerations differed from laboratory tests in terms of duration, peak and shape of the acceleration profile and that these differences affected the postural response of a person. (Kirchner *et al.*, 2014) measured accelerations and decelerations on buses and found, for example that a mean duration for a deceleration event was 9.8s, far longer than experienced in laboratory tests.

The accelerations measured by (Kirchner *et al.*, 2014) were measured in a specific trial by fitting dedicated instrumentation quality equipment to vehicles in service without the bus driver's knowledge. It was not explicitly stated but appeared likely the technique was similar to an earlier study by (Palacio *et al.*, 2009) where a portable system was used surreptitiously by an engineer with a laptop posing as a normal passenger on the bus. Neither study reported the overall distance travelled during data collection, but the study nature suggests it is likely to be relatively small.

(Kirchner *et al.*, 2014) found that peak deceleration was on average over the whole trial 0.19g, (Palacio *et al.*, 2009) did not report an average but used 3 example profiles considered to be representative of typical brake applications as inputs to simulations of the effect on occupants. These were a harsh brake application peaking at 0.32g, a short brake application peaking at 0.16g and a progression from forward acceleration at about 0.14g to a braking deceleration of around 0.04g, more representative of a throttle lifting event than braking.

(Krasna *et al.*, 2021) reviewed similar literature and also noted that many tests did not reflect real bus acceleration profiles. The objective of their study was to collect experimental data to support the development of a realistic human body model to help explore the influences further. Twenty four volunteers were exposed to 5 acceleration pulses in forward and backward directions. Braking pulses of 1 and 2.5 m/s^{2,} with times to peak of 2.2 seconds and 4.4 seconds respectively, were evaluated. Acceleration pulses of 1.5 and 3 m/s^2 were also combined with different jerk rates of 5.6 and 11.3 m/s^3. Volunteers were free standing, not holding onto hand holds. At least one recovery step was needed for more than half of volunteers to maintain balance at 1 m/s^2 and all needed at least one step at higher levels of deceleration. A harness system was used to prevent falls and harness deployment was found to increase sharply between 1.5 and 3 m/s^2. More recovery steps were needed when subjects were backward facing and the deployment of the fall harness was also greater. The study recommended limiting peak acceleration of buses to 1.5 m/s^2 and braking to 1.0 m/s^2 in normal operation and proposed prescriptions for automated vehicles.

All of the above studies associate the low levels of acceleration either measured or tested (0.3 to 3.2 m/s^2) with the prevalence of injuries on board buses that do not experience an external collision. However, (Knight *et al.*, 2019b) found in studies of real passenger falls in service via on-board CCTV recordings of incidents, decelerations of between 1 and 2 m/s accounted for only around 6% of all bus passenger falls. Almost three quarters of passenger falls occurred in incidents with peak decelerations of 5 m/s^2 or more.

The explanation for this apparent discrepancy with the fact that earlier studies did not record these higher decelerations is likely to be the distance travelled. Data collected by (Knight *et al.*, 2019b) showed that decelerations of 1-2 m/s^2 are very frequent with an estimate of around 2.4 billion such events occurring in London's bus fleet each year. These are easily captured in a small trial. The same approach suggested that decelerations in excess of 5 m/s^2 occurred in London only relatively rarely (less than an estimated 45,000 events per year). Thus the (likely) short duration/distance of data collection in earlier studies means that it is probable that it was simply chance that no higher deceleration brake applications occurred during the study.

The findings of (Knight *et al.*, 2019b) strongly suggests that the vast majority of passengers in real life can sustain substantially higher decelerations than suggested by (De Graaf and Van Weperen, 1997) (Kirchner *et al.*, 2014) (Palacio *et al.*, 2009) and (Powell and Palacin, 2015), without suffering falls or injuries considered serious enough for the bus driver to report to allow CCTV to be retained. However, incidents do occur across the acceleration range and so it is possible that, as well as the human's ability to retain balance in the presence of deceleration in those specific incidences, some characteristic of the brake application other than peak acceleration also has a genuine influence on the probability of a fall. If so, then it is possible an AEB system can be designed to minimise the risk of a fall while still achieving the objective of avoiding an external collision risk.

(De Graaf and Van Weperen, 1997) clearly cite rate of change of acceleration (jerk) as a possible factor. This is supported by more research. For example, (Krasna *et al.*, 2021) reported that accelerating was a higher risk than braking due to higher jerk content and recommended including brake jerk in consideration of balance response. However, they also noted results showing an acceleration of 3 m/s^2 caused 90% of backward facing participants to fall into a safety harness compared with 21% in a pulse that had the same jerk rate but only half the acceleration magnitude. This highlights that peak acceleration still has a very strong effect.

(Powell and Palacin, 2015) review the theory of balance and state that where jerk is very high, passengers will not have sufficient time to react, and their behaviour can be approximated by a static rigid body. They define three phases of reaction to retain balance. Low levels of acceleration can be countered by reactions of the lower leg muscles and bending at the ankles, known as the 'ankle strategy'. Larger accelerations also require bending at the hip and higher acceleration still will require one or more steps to be taken to retain balance (hip and stepping strategy respectively). (Powell and Palacin, 2015) state that the minimum time taken to react against external forces is typically around 0.12 to 0.13 seconds but that the time to make larger movements to retain balance is around 1 second. Thus, higher accelerations can be resisted if the occupant has time to make the appropriate reaction.

(Xu *et al.*, 2021) built on this and proposed a further strategy, dubbed the 'fighting stance' where participants initially took a step but then took a longer step with legs further apart and knee bent considerably to lower the body more toward the ground. This was found to be particularly effective at recovering balance.

Based on these observations, hypotheses could be developed that consider the level of acceleration reached 0.12s or 1 second after initial onset to be important determinants in the probability of a fall.

(Powell and Palacin, 2015) also reviewed literature on the effect of acceleration on rail passengers. They cited earlier research suggesting a limit of 1.1 to 1.5 m/s^2 deceleration combined with a max 3 m/s^3 jerk for standing passengers was appropriate. However, they also noted more recent research showing that seated passengers started to be dislodged from their seats at accelerations of 2.45 m/s^2 (1.4 m/s^2 if side facing). (Powell and Palacin, 2015) did not explicitly show the shape of the acceleration curves applied in the tests they cited. However, the use of the term “rise time” could be consistent with a fairly simple linear rise to a peak or to a constant value. (Sarraf, 2011) also undertook laboratory tests on a platform and used an acceleration profile. Although the time base is not shown in the extract reproduced above, the full paper shows that the peak occurred approximately 0.35 seconds after initiation of deceleration, which implies a jerk of 5.7 m/s^3. Of course, technically, this is an average jerk over the whole period of 0.35s and jerk could be calculated as a continuous variable over a much shorter time period. In the case of (Sarraf, 2011), this would make little difference because the increase in acceleration is relatively constant and linear. However, real brake applications tend to be more complex in shape, as shown in the example below taken from the road trial executed for this study and reported in later sections.

Figure 1: Randomly selected example brake application from road trial data recorded during this study

Here the driver has been gently ‘check’ braking for a considerable time before suddenly seeing the need to apply hard braking. At the initial low levels of deceleration, the jerk remains relatively low too. However, the fluctuating nature of the acceleration means that the peak jerk even at this stage can remain higher than the limits proposed by the laboratory testing (up to around 14 m/s^3). When the sudden increase in braking is applied, the jerk reaches 25 m/s^3 and when that is suddenly released again, it goes to minus 48 m/s^3. The fact that higher levels of jerk occur at the release of braking rather than onset appears to be a consistent finding, possibly related to the nature of pneumatic brakes. Air pressure in the brake chamber takes longer to build up than it does to vent to atmosphere, so braking deceleration can be released more quickly than it is applied, if the drivers foot movements are of a comparable speed in both situations.

Overall, these levels of jerk are much higher than those found in laboratory trials. In some cases, the peak values may only occur for a very short time. The laboratory trials do not provide information allowing a view as to whether high jerk over a very short duration has the same or lesser effect on passenger stability. However, in emergency application, the time to peak acceleration will tend to be relatively small with human drivers.

In the above example, the rise time (time from base deceleration to peak) was around 0.5 seconds. Based on the same approach, then this implies an average jerk of 15 m/s^3 (a rise of approx. 7.5 m/s^2 in 0.5 second). More than three times the acceleration increase but in a slightly longer time than the 0.35s seen in the trial of (Sarraf, 2011). In reality, the non-linearities in the shape mean that the true peak is higher still but the peak itself is of very short duration. The jerk only exceeds about 15 m/s^3 for a period of about 0.2s. Again, the research evidence available does not provide any evidence to inform consideration of how important these detail differences are to stability of unrestrained passengers.

It is clear that limiting jerk to the values often seen in the laboratory research (e.g. $<6m/s^3$) would result in emergency levels of deceleration taking much longer to be reached. In the example above, an average jerk limit of 6 m/s^3 would imply a brake rise time of 1.25 seconds, 0.75 seconds more than the human driver actually delivered. If the limit was applied to peak jerk, then non-linearities in the system would delay peak braking achievement further. This would significantly limit the ability of either a human driver or AEB to avoid a collision, particularly of a pedestrian crossing type where the available time is short.

Thus, consideration of the strength of evidence to support an increasing risk is very important, as is consideration of how to optimise braking to maximise benefits and minimise risks:

- Is it better for passengers to reach a low deceleration fast or a higher deceleration more slowly?
- Is there any merit in limiting acceleration or jerk only for the time it takes for a human passenger to react (<0.15s for initial muscular strategy, c. 1s for a stepping strategy)? The “elbow” in the graphs shown in (Powell and Palacin, 2015) might support that theory.
- If a deceleration is large enough to cause a stepping strategy from a passenger to prevent a fall, but the deceleration is removed again before 1 second is reached; does this reduce the chances of a fall?
- Alternatively, given that releasing the brakes might create a higher jerk than applying did, does this increase the chances of a fall, especially given that the jerk is in the opposite direction to that at the onset of braking? If it does, then could the effect be mitigated for AEB by slowing the release of the brakes?
- The laboratory research appears to focus on peak acceleration and jerk. However, as acknowledged by several authors, braking and acceleration pulses in the real world last for much longer than is possible to easily reproduce

in a laboratory. From a passenger's frame of reference, their centre of gravity will move at the same speed and the bus slows down underneath them, which seems like the floor moving backwards underneath them. The distance it moves backwards, and potentially the steps that need to be taken to retain balance, will relate to duration of braking as well as deceleration.

Currently, these questions cannot be answered by laboratory test methods. This project has attempted to provide answers by collecting empirical data from the field around brake jerk, duration and change in velocity and the results are presented alongside those for peak decelerations in the subsequent sections.

2.2 Summary of prior research on bus AEB

Phase 1 of TfL's development of the Bus Safety Standard (BSS) analysed the effects of AEB (Knight *et al.*, 2019) (Knight *et al.*, 2019b). Modelling was used to estimate the benefits of collisions avoided (with vehicles, pedestrians, cyclists).

(Knight *et al.*, 2019) studied the benefit of AEB in true positive situations based on a combination of analyses of incidents in both police fatal collision data, operator CCTV incident data and analyses of the test results on the prototype vehicle. A case-by-case analysis was undertaken to assess whether each incident could have been prevented by AEB performing as per the prototype system and several hypothetical variations of that performance level. As such, it was a prediction of what AEB might be expected to do in the absence of any concurrent changes associated with driver or other road user behaviour etc. This is the best that can be achieved when a system is not yet fitted to enough production vehicles to allow a measurement of the actual collision involvement rate of vehicles with the system compared to those without. Although no study is perfect, this was considered adequately robust for the purpose and of a comparable standard to many other analyses underpinning important road safety decisions. As such, no additional analyses were considered necessary in this project to specifically improve the robustness of the true positive benefits and the fundamental effectiveness estimates have been based on the findings of (Knight *et al.*, 2019).

The most contentious part of implementing AEB on buses is the perceived risk to bus passengers posed by false activations. The previous modelling also estimated the disbenefits of injuries caused to bus passengers by false AEB interventions. The 'balance' of benefits versus disbenefits is described in Figure 2.

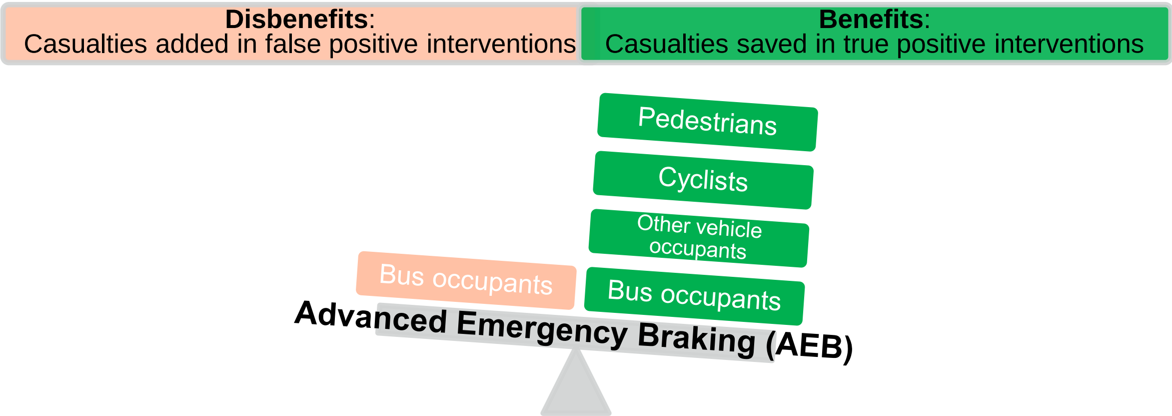


Figure 2: Illustration describing the casualty types involved in the benefits and disbenefits of AEB

There were several key steps to estimate the number of bus passenger casualties caused by AEB false positives. First was to quantify the number of times that buses experienced deceleration events in normal service, either from the driver applying the brakes or from a “throttle lift event” resulting from engine braking when the driver released the throttle (or regenerative braking in the case of hybrid and electric vehicles). This was measured during a short road trial with accurate instrumentation covering 400km. It was clearly identified that gentle deceleration events were very frequent but peak decelerations above 2 m/s^2 were much rarer. The heaviest brake application experienced during the trial was around 3.5 m/s^2 and no emergency brake applications were experienced. The results of the trial were extrapolated to generate a full distribution of brake events from gentle to emergency level, as shown in Figure 3, and it was assumed that this distribution applied to all 490 million bus km travelled each year in London.

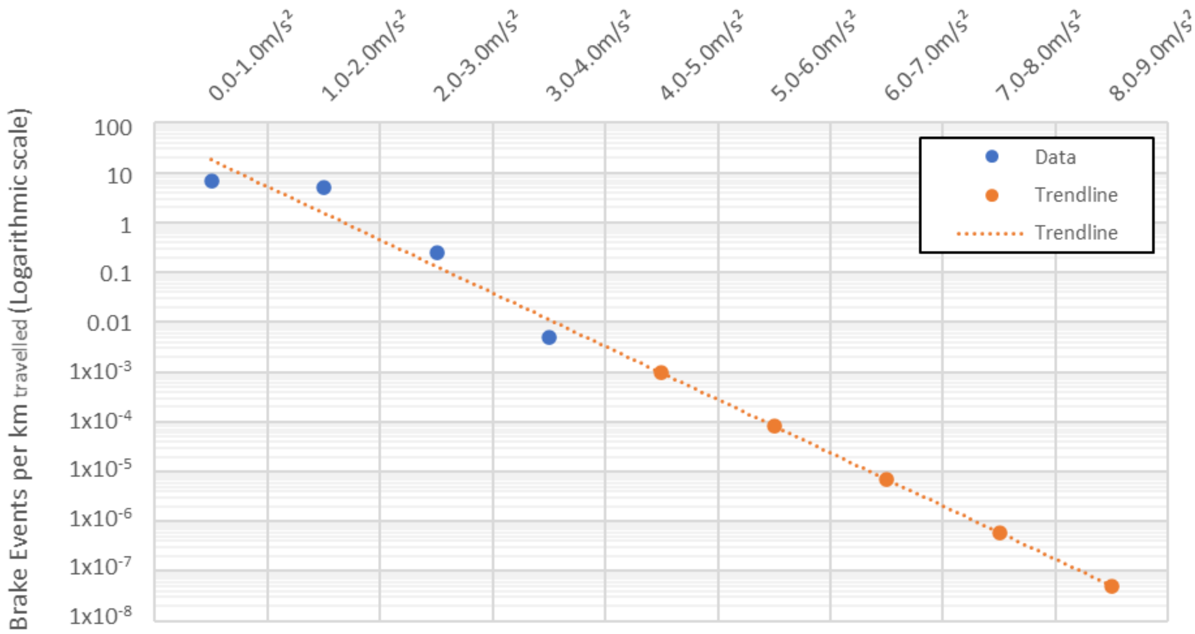


Figure 3: Frequency of deceleration events per km travelled by peak deceleration group; extrapolated for higher deceleration groups (Source: Knight et al, 2019)

CCTV clips of braking incidents (which included vehicle deceleration data) were then used to derive a function of the proportion of passengers on the bus that fell and were injured by vehicle deceleration. 'Falls' were defined as the cases when a person fell to the floor or that substantially moved under braking (i.e., more than just rocking in their seat) to the point of contacting another surface. For simplicity, these are referred to as "falls" throughout the rest of the document.

It was assumed that this function could be applied to all bus occupant casualties identified by IRIS occurring due to slips trips and falls where the primary cause was listed as braking.

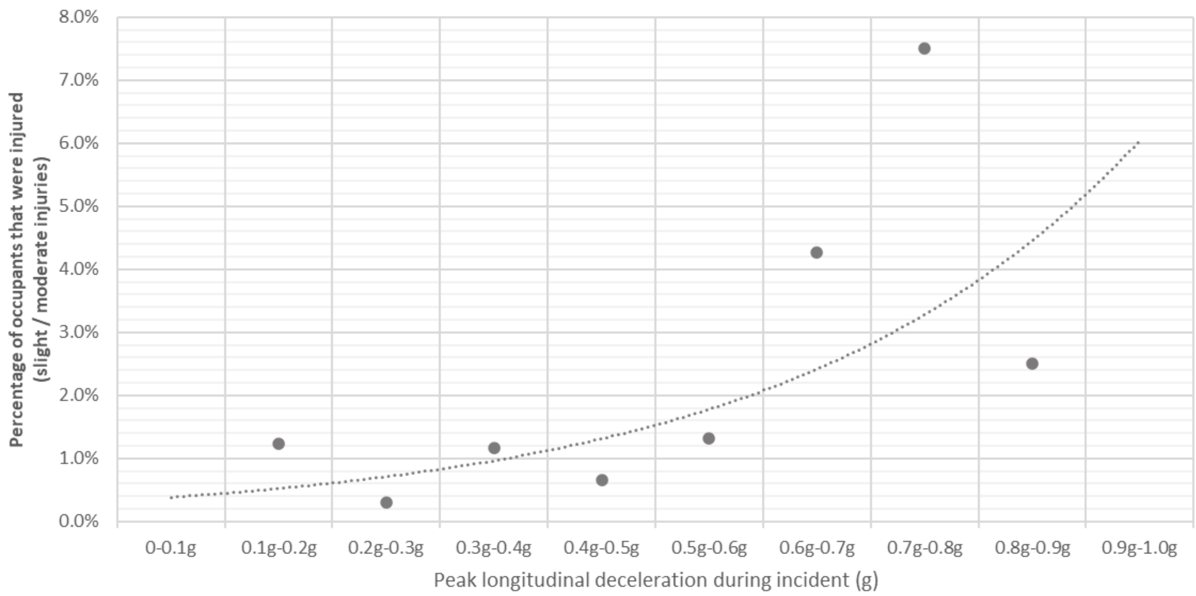


Figure 4: Proportion of bus occupants injured during deceleration by peak deceleration group (Source: Knight et al, 2019)

It found that at low levels of deceleration, less than 2% of bus occupants were injured from the sample of collisions involving braking (Figure 4). This proportion increased at higher levels of deceleration, but the sample size was quite small leading to some uncertainty about the accuracy of those numbers.

Figure 5 also shows that, of the occupants that were injured, only about 6% of such casualties were at low levels of deceleration (1-2 m/s^2) and around 60% occurred at decelerations greater than 6 m/s^2.

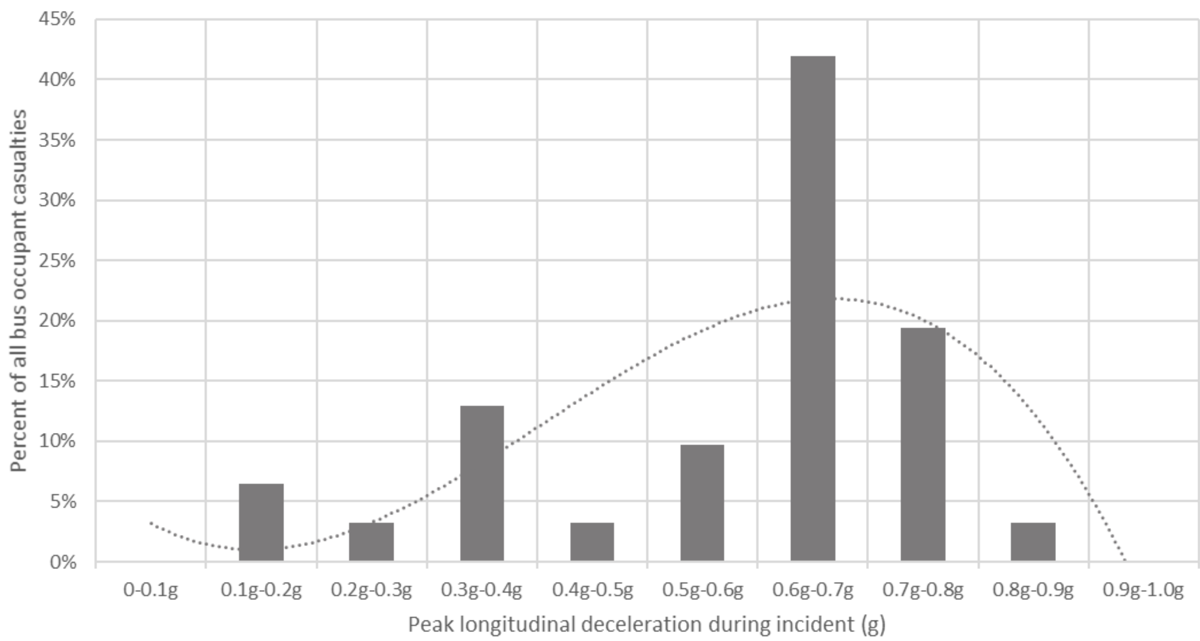


Figure 5: Breakdown of bus occupant casualties by peak deceleration group (Source: Knight et al, 2019)

The frequency of brake applications at a given level of deceleration was combined with information on the number of casualties that occurred from incidents of braking at that same level of deceleration to produce an estimate of the risk of injuries per brake application. It was found that this risk was extremely low at low levels of deceleration (1-2 m/s^2) but, on average, a casualty was likely to occur almost every single time a bus braked at the highest levels of deceleration.

When all the individual benefits and disbenefits associated with each casualty type were combined, the resulting cost-benefit analysis showed that the fitment of AEB had potential to offer strong benefits. Three variants of AEB were assessed[1] and it was found that the benefits were sensitive to the frequency with which a false positive occurred and the peak deceleration achieved by the system (Figure 6).

[1] AEB_High allowed a peak deceleration of $9m/s^2$, for AEB_Mid the peak deceleration was capped at 7 m/s^2, and for AEB_Low the peak deceleration was capped at 5 m/s^2

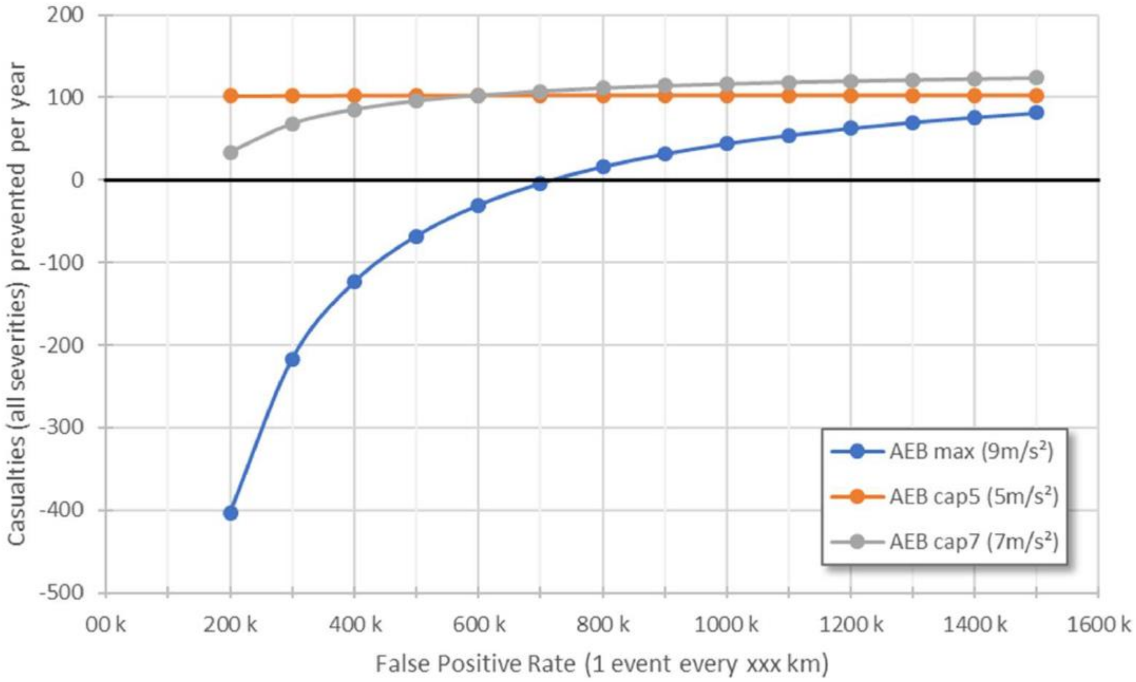


Figure 6: The effect of false positive rate on the net casualty benefit of each candidate AEB system (central prediction) (Source: Knight et al, 2019)

Equivalent graphs were also considered for the effects on fatalities only and the effect on the net monetised benefit of all casualty prevention. On this basis, a limit was proposed for the bus vehicle specification to require false positive activations at an average rate of no more than 1 every 600,000-bus km. That is, an average bus with AEB should be able to drive for at least 600,000km before a false positive occurs. This was selected because, although Figure 6 indicates that there would be a small net disbenefit on the total number of casualties, the analysis showed that at rates better than 1 in 600k the 'max braking' approach would offer the best possible benefit for fatalities, the net monetised benefit remained strongly positive at that point and it recognised the potential technical challenges that might be involved in meeting the requirements with a new technology for M_3 buses with standing passengers, based on stakeholder input. It was also based on the understanding that TfL would have the flexibility to make the standards more stringent at some point in the future.

It was recognised that the above analysis was dependant on three key input parameters, which were weakly based:

- Frequency of bus occupant casualties under different levels of deceleration,
- Frequency of heavy brake applications ($5m/s^2$+) in real service, and
- The correlation of occupant injury potential to peak deceleration only, not jerk, event duration or change in speed

Thus, the principle aim of this study was to directly address those weaknesses to validate or amend the original results and thus provide a greater degree of confidence in the results.

2.3 Objectives of this study

Several key objectives were identified for this study. They are briefly described below and are explored in greater depth in the subsequent section of the report.

1. The first objective was to validate, or amend if necessary, the previous finding that AEB would provide substantial net casualty benefits on buses in London if it experienced false positive activations at an average rate of 1 every 600,000-bus km or longer. This involved substantially increasing the robustness of the core input data for both incidents (CCTV analysis) and naturalistic braking behaviour by increasing the sample size and the coverage to include different London bus routes and operators.
2. To assess the extent to which a net change in overall casualty numbers might mask a disproportionate change in the level of risk for different groups of the population. This involved disaggregating the output of the modelling to, for example, compare if younger/fitter cyclists benefit at the expense of more elderly bus occupants.
3. To analyse, as far as possible given the limitations of the data available, the potential effect of additional braking variables on the probability of passenger falls or movement under braking that leads to injury, namely initial speed at start of brake application, change in speed during braking, average deceleration, and rate of change of deceleration (jerk).
4. All the work conducted during the Phase 1 BSS research on AEB had been conducted before the COVID-19 pandemic. The pandemic caused severe disruption to travel patterns and so it was important to assess whether the original findings were likely to remain valid in different scenarios of post-pandemic bus provision and use and vulnerable road user traffic.
5. A final objective was to provide materials to support the development of AEB within the bus industry, specifically to provide information that the industry will find useful, particularly in developing their cases to demonstrate functional safety and safety of the intended function in accordance with international standards. The reason for this objective is that successful implementation of AEB is likely to require significant investment and development from industry to bring technologies to market. Manufacturers have stated that the data generated by the previous research was useful to them, so TfL wish to help facilitate AEB system development by providing outputs generated by this research.

3 Frequency of bus occupant casualties (CCTV analysis)

The incident data for the original BSS study was past cases that all came from one London bus operator. This study has firstly continued working with that operator to add more cases. Secondly this study has also expanded to use two additional London operators and covers more recent cases, most of which are post pandemic (since March 2020).

3.1 Database design

The previously used incident data was defined for different purposes to that of the current project. As such, a new incident database was defined and constructed with the aim of allowing efficient data coding for a distributed coding team as well as for easy analysis and backward compatibility with the earlier data.

The database comprised of three main sections. First there was a single record for each incident the included high-level information such as date, time, the number of vehicles and casualties involved and whether the incident was suitable for further coding. For each incident linked records were created that provided further details of the vehicles involved and resulting casualties (Figure 7).

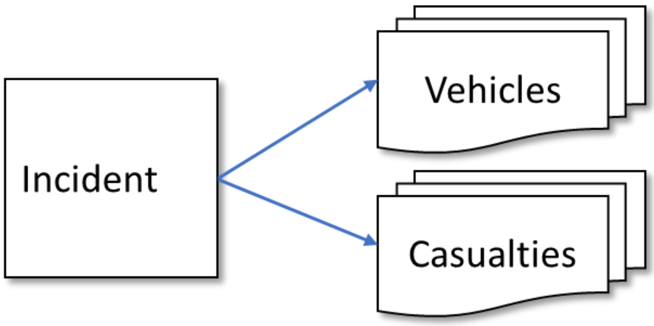


Figure 7: High-level CCTV database schema

The Vehicles table included information such as the type of vehicle, details of any impact and, for the bus involved, details of the travel speed, timing and magnitude of deceleration experienced during the braking event. The number of occupants that were onboard, affected by the braking or injured were recorded including details of their seating configuration.

Further detail on each of the bus occupants affected or injured during the incidents were recorded in the Casualties table. This included basic information about their gender, age group, any obvious impairment, and the estimated severity of their injury. More details on their location within the bus, direction of seating and of any objects held/hit during the incident were also captured.

A copy of the tables/fields/data structures as appropriate are included as Appendix A.

3.2 Accuracy of data from CCTV systems

(Knight *et al.*, 2019) characterised the conditions when bus occupants fell under braking based on a small sample of 80 incidents all occurring before the pandemic. One of the key outputs was a frequency distribution of the number of occupants injured by a slip trip or fall during a braking event compared with the peak bus deceleration at the time of fall. This relied completely on the accuracy of the acceleration data recorded in some, but not all, of the CCTV recordings for each incident.

As part of this update, a series of short tests were undertaken to compare the CCTV records with a more sophisticated inertial measuring system intended for research and development purposes. It should be noted that these were specific tests using buses that were out of service and carrying no passengers except for the test engineers.

A sample of CCTV systems were assessed by installing a Racelogic VBox 3i with IMU (Inertial Motion Unit) to measure speed and acceleration in buses alongside the existing CCTV system.

The following three vehicles were tested:

Vehicle 1 was fitted with PCPlayer CCTV system. This system displays speed and acceleration data on a time history graph (Figure 8).

Figure 8: Screenshot from PCPlayer CCTV system

Vehicle 2 was fitted with SynxViewer CCTV system. This system displays speed and acceleration data as a numeric overlay on the video image. Activation of the brake pedal is shown by a red rectangle in the image, as illustrated in Figure 9.

Figure 9: Screenshot from SynxViewer CCTV system

Vehicle 3 was fitted with a MediaPlayer2 system. This system displays speed and acceleration data as a numeric overlay on the video image. Activation of the brake pedal is shown by the word “Footbrake” in the image (Figure 10).

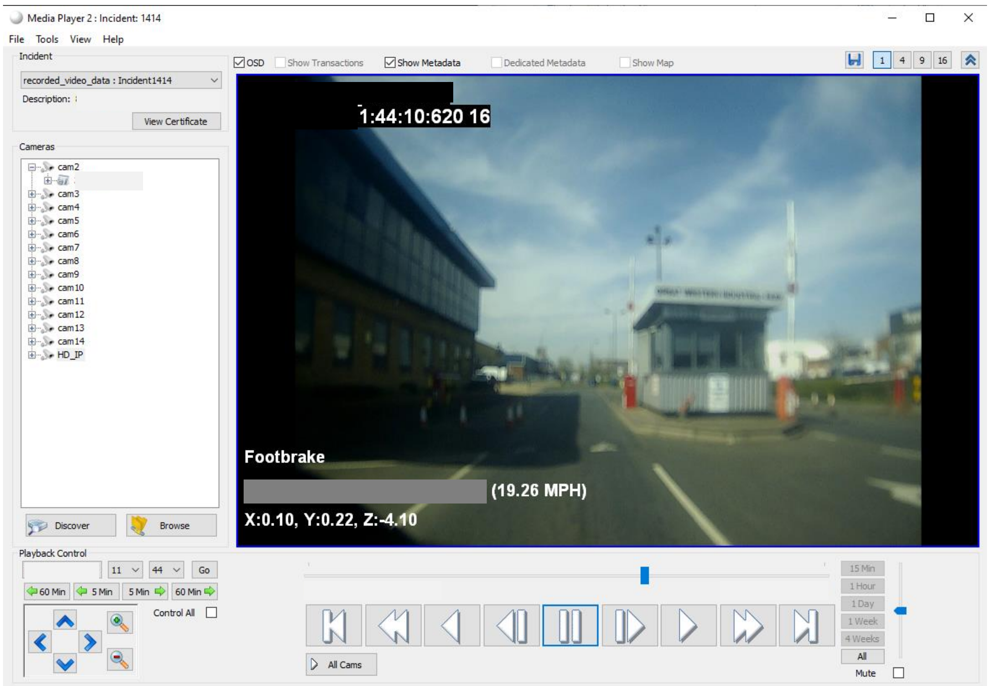


Figure 10: Screenshot from MediaPlayer2 system

For each vehicle, a series of brake tests were conducted on local roads close to the depot. The results produced by the CCTV system were compared to those of the Racelogic system. The braking events ranged from brief “check brake” events, where the brake pedal is only pressed momentarily before being released, to gentle brake applications typical of normal service and emergency brake applications.

For each event, the timing, vehicle speed and magnitude of deceleration was noted and compared to the data recorded by the Racelogic system. Three key metrics were compared:

- Duration of the braking event
- Peak deceleration
- Time to peak deceleration

3.2.1 Accuracy of the duration of braking event.

Perhaps unsurprisingly, there were significant differences between the systems on the CCTV and the instrumentation quality approach and differences of more than 1 second were observed. However, overall, the duration of the braking events observed by the CCTV systems was broadly in line with the durations recorded by the Racelogic (Figure 11) and can be considered approximate but generally a good indication. It was observed that if the CCTV footage was viewed with multiple cameras playing at the same time then the timestamp displayed on each camera was slightly different. This highlighted the importance of using a single camera view when coding the cases to ensure the relative timing of the start, end and peak deceleration remained constant.

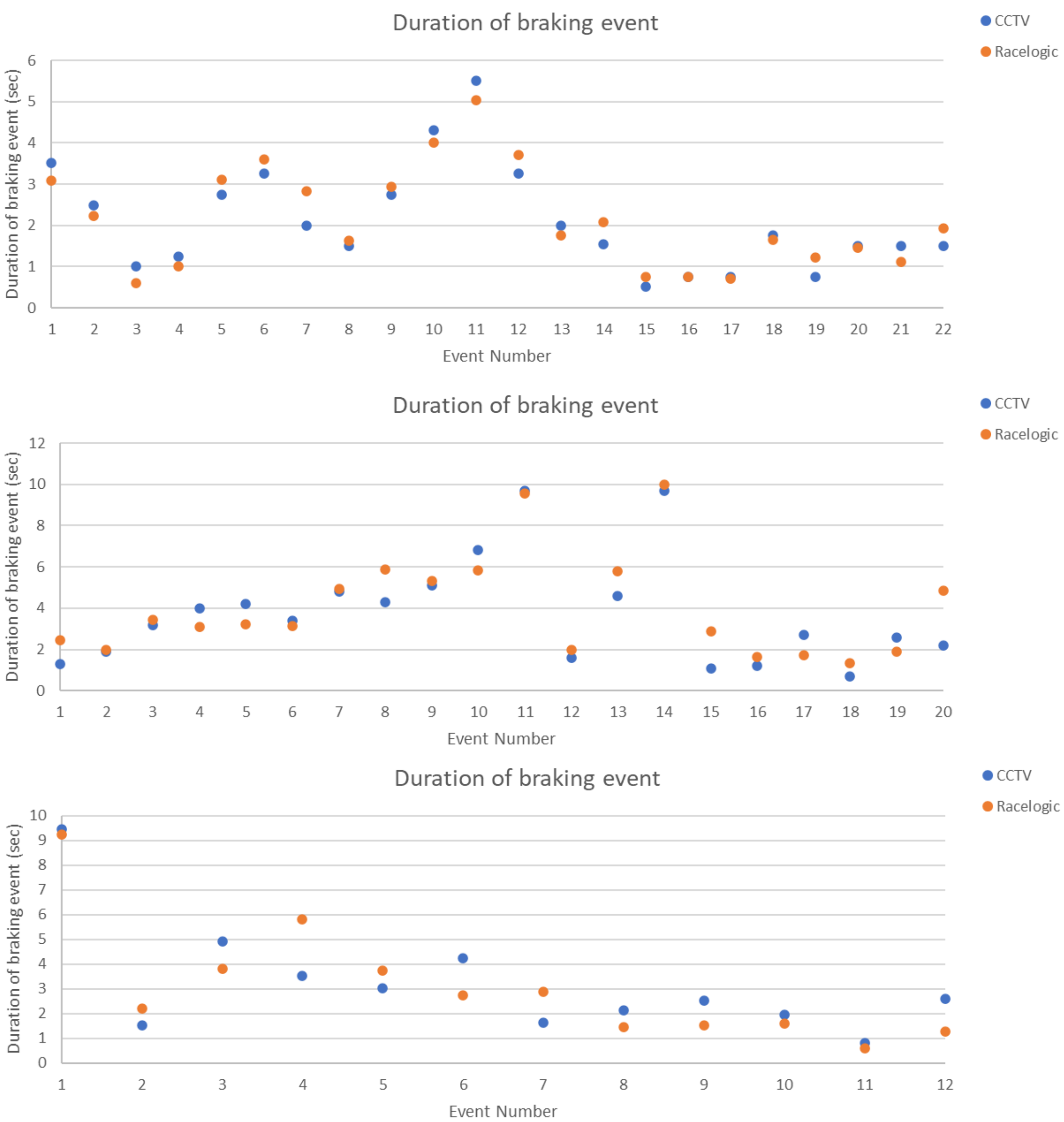


Figure 11: Comparison of brake event duration recorded by Racelogic and CCTV systems (Top: PCPlayer, Middle: SynxViewer, Bottom: MediaPlayer2)

3.2.2 Accuracy of peak deceleration

Again, it is clear that acceleration measurements from the CCTV systems are imperfect and differences were observed. The resolution of the time history graph offered by the PCPlayer system provided broadly similar peak values to those recorded by the Racelogic system. Determining the peak deceleration for the CCTV systems with the acceleration data presented as a text stream on the video image was found to be much harder. Despite that limitation, the peak values observed from these systems were broadly in line with the Racelogic data.

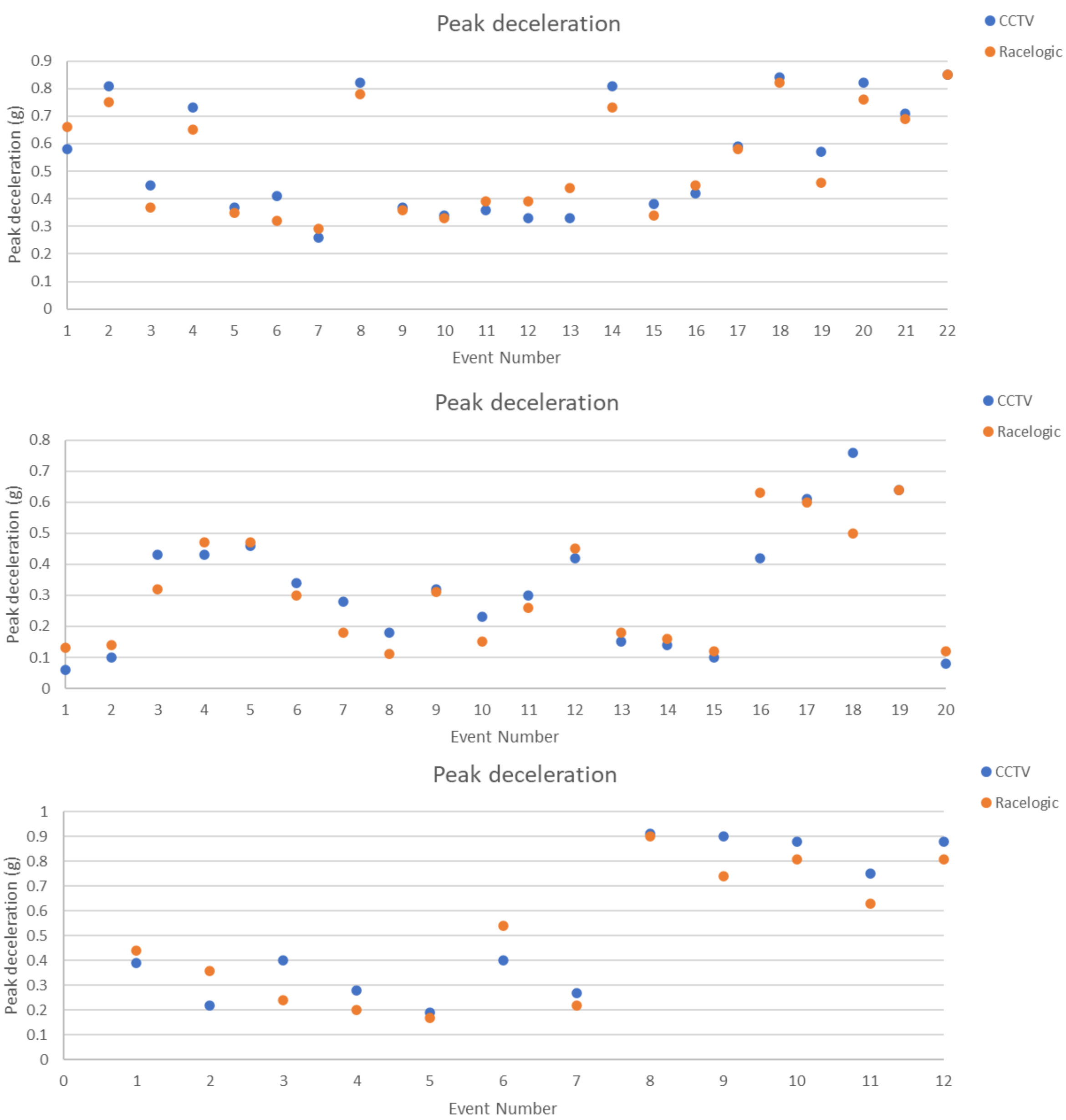


Figure 12: Comparison of peak deceleration recorded by Racelogic and CCTV systems (Top: PCPlayer, Middle: SynxViewer, Bottom: MediaPlayer2)

One of the reasons for undertaking "check" braking events was to see if the refresh rate on the CCTV systems was sufficient to display the correct peak deceleration value when the overall duration of the braking event was very short (< 1 second) or whether the time interval between samples was long enough to miss the absolute peak. The results shown in Figure 12 show a reasonable correlation between the peak values recorded by both the Racelogic instrumentation and the CCTV systems and it was possible to identify the peaks during brief "check braking" events.

So, overall the finding is similar to duration. Significant inaccuracies do exist and results should be considered approximate but they are reasonably indicative of the real situation. Importantly, there did not appear to be any systematic biases in one direction such that across a large population of incidents, the inaccuracies that do exist would not be expected to be a substantial problem.

3.2.3 Accuracy of time to reach peak deceleration

The time to reach peak deceleration was defined as the difference between the timestamp when the brake pedal was first pressed (or first displayed on the CCTV image) and the timestamp at which the maximum value of longitudinal deceleration was measured.

The charts in Figure 13 show that the CCTV systems with data overlayed on the image tended to display a peak value earlier in the braking event compared to the Racelogic. This might be related to the synchronisation between the data and image because the speed was also observed to be out of sync, for example, in some cases the video had shown that the bus was stationary, but it took several frames before the displayed speed also showed zero.

This is an important consideration because if the CCTV system suggests that the peak has occurred sooner than is the case, this would imply that jerk is higher than it is in reality.

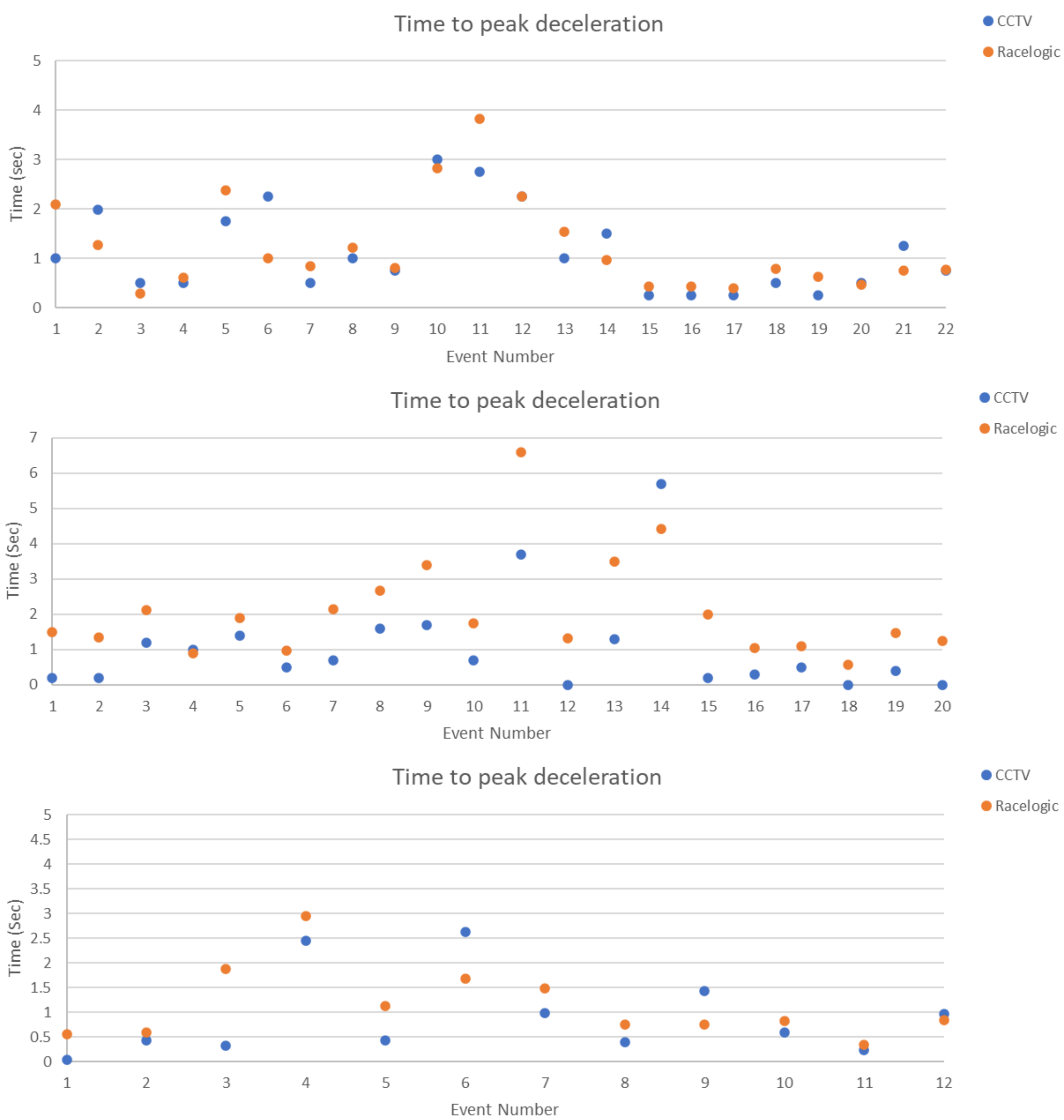


Figure 13**: Comparison of time to peak deceleration recorded by Racelogic and CCTV systems (Top: PCPlayer, Middle: SynxViewer, Bottom: MediaPlayer2)**

3.3 Scope of data collected

The target was set to accumulate a total of 300 cases where the bus was braking and occupants fell, and the CCTV included acceleration data. This comprised the 63 relevant cases from the Phase 1 study and an additional sample of 238 cases (301 cases in total), representing an increase in sample size of almost four-fold.

Table 1: Overview of CCTV sample

	Phase 1 BSS		2021 Sample		Combined	
Number of incidents	63		238		301	
Total number of occupants	1,644		3,190		4,834	
Average bus occupancy	26.1		13.4		16.2	
Occupants injured	31	1.9%	142	4.5%	173	3.6%

Data from the latest sample suggests that the proportion of those that were on board at the time and that were injured during a braking incident is more than double that for the original sample. However, it should also be noted that the number of occupants on board at the time of the incident was around double in the original sample (26.1 occupants per bus) than it was in the 2021 sample (13.4 occupants per vehicle). It can be observed from both samples that when incidents occur it is most frequently only a small number of passengers on board that are adversely affected, often only 1 or 2. Mathematically if this same 1 or 2 per incident are divided by half the total number of occupants (on average) then a doubling in the proportion injured would be expected. However, it is not known if this is the only influence behind the increased proportion of whether some other change in the characteristics or behaviour of passengers still using the bus, or if a change in the road environment, post pandemic is of influence.

A breakdown of the occupants and casualties from the latest data (Table 2) shows that by far the greatest number of passengers injured under braking were correctly seated. However, this was a function of the exposure to risk. There were simply many more correctly seated occupants than there were, standing occupants etc. The proportion of occupants that were injured when they were seated in an orthodox position was much lower than for other categories, indicating a much lower risk per passenger. Standing passengers had a much higher risk and those seated out of position (e.g., sideways in a forward-facing seat) had a similar risk of injury to standing occupants. Occupants that were moving within the bus or transitioning between sitting and standing had the greatest risk of injury. Note that the numbers of transitioning and moving occupants were very small, so should be treated with a little caution.

Table 2: Proportion of bus occupants injured by seating position

	Seated (In position)	Seated (Out of position)	Standing	Transitioning	Moving	Total
Occupants	2787	50	261	26	66	3190
Injured	78	7	35	8	14	142
% Injured	2.8%	14.0%	13.4%	30.8%	21.2%	4.5%

This highlights another factor that may influence the risks of AEB over time. The risk of injury per passenger (% injured in Table 2) is much higher for standing passengers than for correctly seated passengers. Thus, if the total number of passengers carried on a bus remained the same, but a higher proportion were standees, then the casualty risk from any kind of brake application is likely to increase. In order to aid social distancing, bus passengers were advised to use the seats that remained open rather than standing during the pandemic. The extent to which passengers complied with this advice has not been quantified. However, the expectation would be that if a lower proportion of passengers were standing the proportion of passengers injured under braking would decrease. In fact, the data suggests an increase as reported above, strongly suggesting more than one factor influenced this change.

3.4 Characterising bus occupant injuries under braking

Two key relationships were used from the Phase 1 study for the calculation of the effect of false positives:

- Proportion of occupants injured by peak deceleration
- Proportion of casualties injured by peak deceleration

3.4.1 Proportion of occupants injured by peak deceleration

In the Phase 1 study, the results (Figure 14) showed that the proportion of occupants on board that were injured in a given incident tended to increase as the peak deceleration increased. There was some uncertainty about the figure for the high levels of deceleration due to substantial scatter in the data, initially attributed to the small sample size.

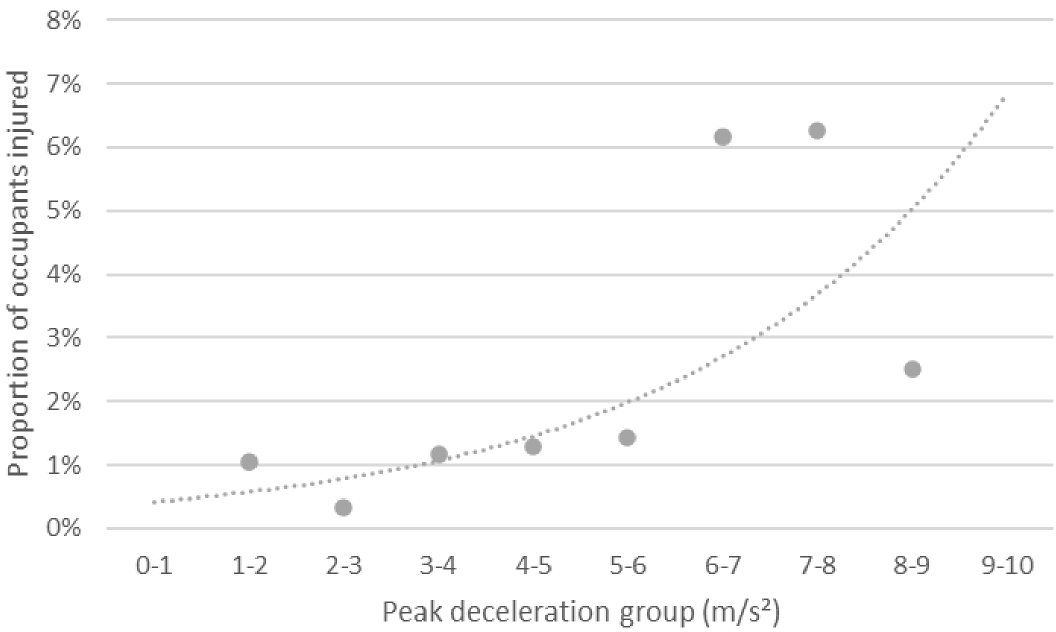
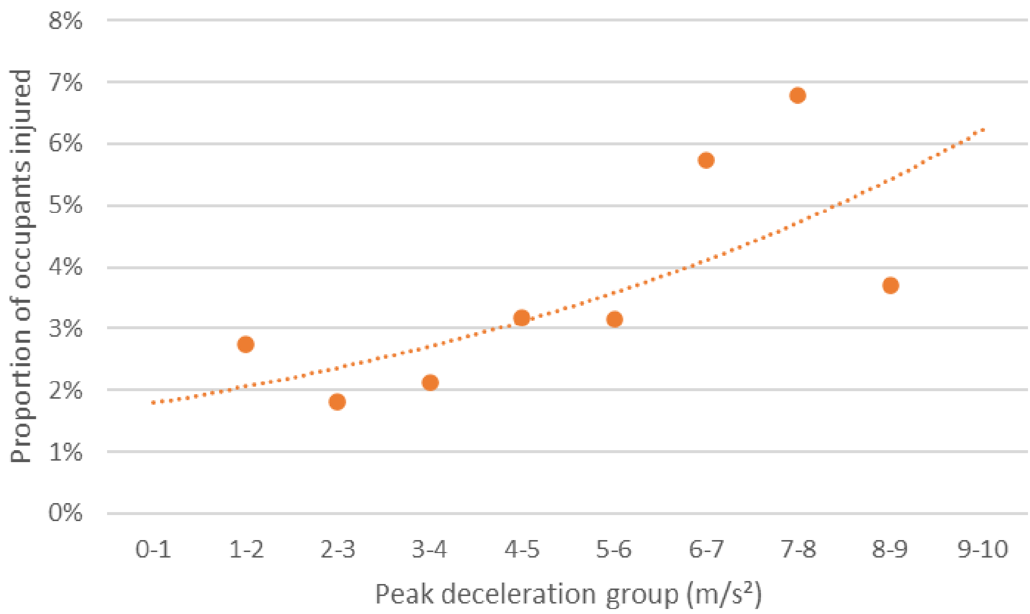


Figure 14: Proportion of bus occupant casualties injured under braking – Phase 1 result. (n = 63) (Source: Knight et al, 2019)

The latest data captured during this study was combined with the original data from Phase 1 to produce an updated relationship (Figure 15). Overall, the chart shows that at lower levels of deceleration a slightly greater proportion of occupants are injured than originally estimated in Phase 1, but the rate at which that increases at higher levels of deceleration is lower than suggested from the Phase 1 study. The increased sample size does not appear to have substantially decreased the scatter at the high levels of deceleration. This may still be random chance. Viewing CCTV videos of people falling on buses shows that in many cases it is not obvious why one or two people fell and the remaining 10, 20 or more did not. Certainly, it is often not as simple as standing or sitting, holding on or not, or using a mobile phone. However, it may also be that there is some physical reason or systematic bias behind this result. It could be speculated that in general all brake applications above 6 m/s^2 were full emergency brake applications but certain types or ages of bus were not capable of achieving 8-9 m/s^2. Similarly, some of those might have occurred in wet conditions prompting ABS activation at lower decelerations whereas in dry conditions higher decelerations were achieved without ABS activation. However, no data is available to quantify these possibilities.



Group	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
Cases	0	29	45	48	38	36	41	41	21	2

Figure 15: Proportion of bus occupant casualties injured under braking – combined result from the Phase 1 study and this latest project (n = 301)

3.4.2 Proportion of casualties injured by peak deceleration

Once it is understood what proportion of all occupants are injured during braking incidents, the next relationship to update was the breakdown of those casualties by the value of peak deceleration.

The result from the Phase 1 study showed that over 40% of casualties occurred when the bus had a peak deceleration of 6-7 m/s^2, with a lower and more consistent distribution across the other deceleration groups (Figure 16).

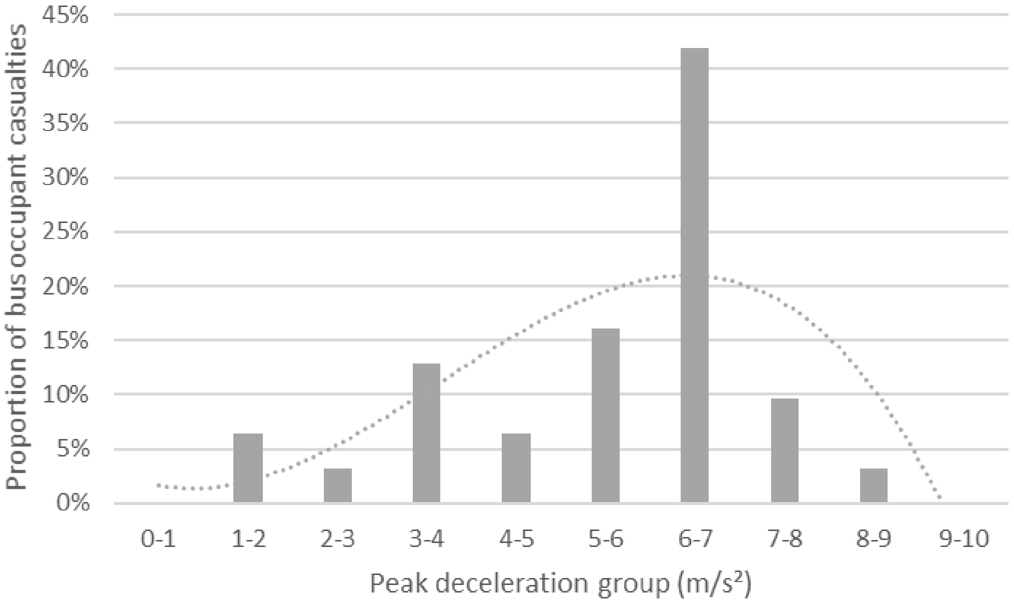


Figure 16: Relationship between the proportion of all casualties under braking and the peak acceleration involved. (n = 63) (Source: Knight et al, 2019)

As above, the latest data collected from this study was combined with the original result to produce an updated relationship (Figure 17).

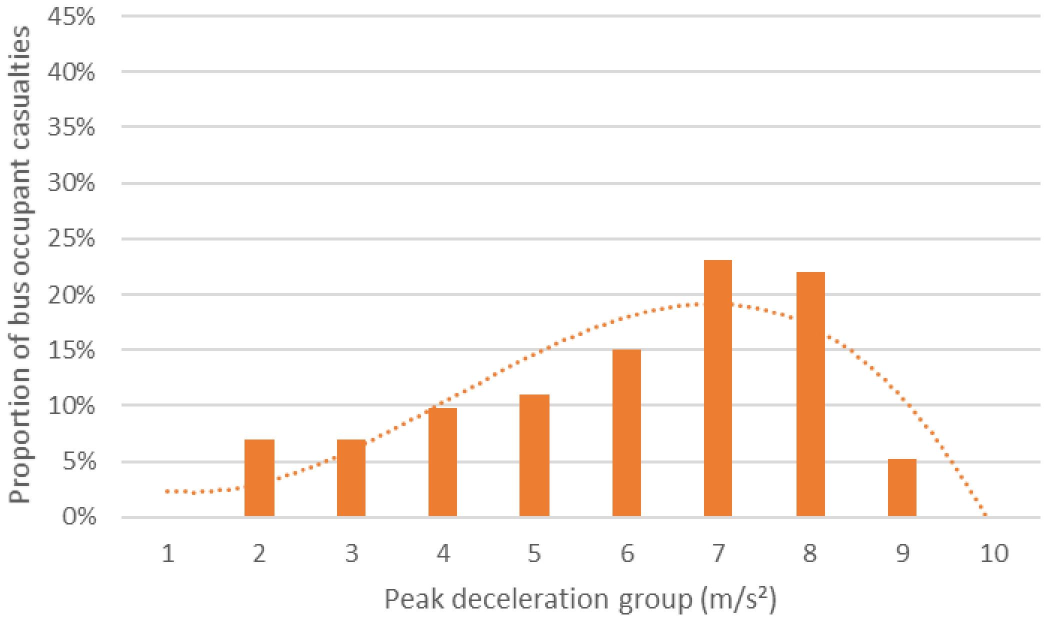


Figure 17: Relationship between the proportion of all casualties that occurred under braking and the peak acceleration involved. Combined result from the Phase 1 study and this latest project (n = 301)

The latest data showed a much more consistent distribution with gradually more occupants injured as the peak deceleration increased. As a result, the combined set of data shows a more even distribution across the deceleration groups with incidents with a peak deceleration of between 6 and 8 m/s^2 producing 45% of all casualties. The trendline shown in Figure 17 is very similar to that of the original data set, although the new data now means it is a better fit than before.

4 Frequency of brake applications in service (telematics)

In the original trial, the bus used was a prototype equipped with AEB and two different data acquisition systems, the first a complex and comprehensive manufacturer specific system that could fully access all the AEB operation and data to assess what the system was doing. The second was a simpler system, though still sophisticated, combining GPS speed and distance measurement, video and logging of vehicle CAN bus channels. The bus could not be put into service, two engineers were always on the bus to monitor the equipment and make manual notes and data was manually downloaded for subsequent analysis. All of this was a reasonable approach for a short duration, in-depth trial covering only 400km.

However, the target for this project's trial was to collect at least one million bus km of driving in order to represent a high likelihood of capturing a significant number of high deceleration braking events, including at least one at maximum deceleration. The same approach would be neither practical, nor cost effective for such a large trial.

It was, therefore, decided to seek bus operators or telematics providers that could provide the data using simpler, cheaper data acquisition devices that are routinely used unsupervised to collect fleet management data for operators and transmit that data to a cloud service over the GSM[2] network to remote servers. Systems are typically set up such that the on-board device monitors its sensors and inputs continually and undertakes real-time analysis to identify certain pre-programmed events. The source data is then discarded and data about each detected event is sent via the telematics to the remote server and recorded. Such events could include switching the bus on or off, a time-based event (e.g., status of inputs sent once every second, or once every minute), or it could relate to a driver action such as braking.

Most fleet management systems will be set up to report harsh braking as an event. However, this means that an event will be recorded every time a harsh braking event occurs, and this is defined as an acceleration more than a single threshold which may often be set at around 2 or 3 m/s^2. For this project, this did not provide enough differentiation to be useful. The previous analyses categorised peak deceleration in 1 m/s^2 bands as shown below:

0-1m/s^2	1-2m/s^2	2-3m/s^2	3-4m/s^2	4-5m/s^2	5-6m/s^2	6-7m/s^2	7-8m/s^2	8-9m/s^2

In addition to this, most systems do not sample the sensor inputs at particularly high frequency, 10 Hz being a common maximum. One of the objectives of this study was to consider different braking variable including the rate of change of acceleration (jerk). To do this accurately requires a higher sample rate, and realistically 10 Hz would be an absolute minimum value to be feasible, 100 Hz would be ideal.

It was considered highly desirable that the data was collected over a range of routes, vehicle sizes and powertrain types considered broadly representative of the London

[2] Global System for Mobile communications

fleet. Finally, given that this data collection exercise was large scale and expensive, it was also considered desirable to record any factors that could be collected without significant additional cost or effort that could add value to the data set, for its use in this, or other future safety or environmental analysis projects.

4.1 Trial design

21st Century Fleet Systems were able to offer their Journeo telematics solution that could provide a sampling rate of approximately 30 Hz and was able to send all data back to the servers such that it could be provided in a 'raw' stream of data that the project team could use for any type of post processing required.

This solution also had the advantage that the company already supplied CCTV and other fleet systems to the bus operator selected to collaborate with the project. This meant that they knew the fleet operation well and could share some of the hardware with other systems and some aspects of configuration were already undertaken.

The solution was able to record all the required measures including acceleration in each direction, pedal activations, vehicle speed and location and offered the additional functionality of being able to download CCTV clips of incidents identified in the data.

The data collection began in February 2021 with a short pilot phase and the rollout progressed until 50 buses were collecting correct data at the end March 2021. Data was collected until the end of August 2021. This data was considered representative of the tail end of the COVID-19 pandemic lockdown period and the early phases of any post pandemic 'new normal'.

4.1.1 Consideration of existing fleet mix

Using data published by TfL[3] it was identified that over half the London bus fleet use diesel engines, approximately 40% use a hybrid engine and a small proportion are electric vehicles.

The bus operator provided a list of the routes they operate, and the individual buses assigned to each route. From this it was possible to select a range of routes that provided a similar engine-type distribution to the current TfL fleet, that covered a range of geographical areas within Greater London Authority (GLA) (Figure 18) and fitted with the bus operators' operational requirements.

[3] http://content.tfl.gov.uk/fleet-audit-report-31-march-2020.pdf

Table 3: Distribution of trial vehicles compared to current London distribution

	Electric	Double Deck Hybrid	Single Deck Diesel	Double Deck Diesel	Total
Current TfL distribution	3%	41%	26%	29%	100%
Trial distribution	10%	48%	30%	12%	100%
Number of test vehicles	**5**	**24**	**15**	**6**	**50**

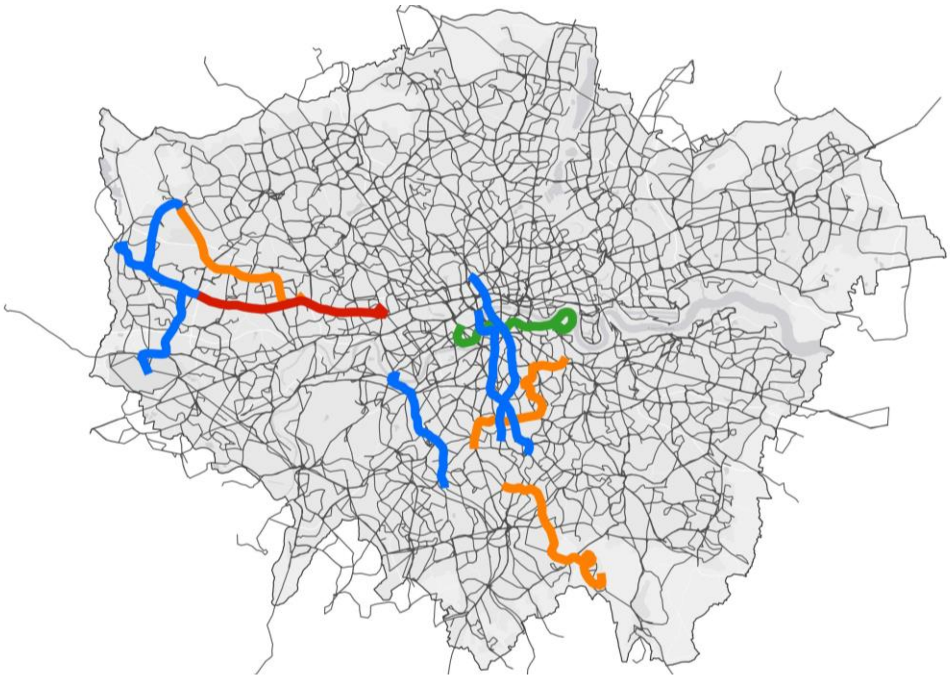


Figure 18: Selected routes by engine types and location

4.2 Data processing and cleaning

The raw telematics data was delivered in simple CSV format with, on average, 50 files delivered per bus per day with each file covering a period of approximate 15 minutes of driving. Automated programmes were written to import the large numbers of files into an SQL database. In total over 350,000 files were processed and more than 12 million deceleration events identified from those files.

The post processing was broken down into two main stages:

- Event identification: The first set of analysis routines processed the raw time history data into an 'event' data set that had one line of data for every deceleration event and was stored in a database of more manageable size.
- Event analysis: Each identified event was then analysed to produce the 'results' data that formed the input to the naturalistic driving element of the benefit - risk model.

4.2.1 Event identification

Each raw file contained a time history of the movement of the bus. Some basic processing was completed to identify and exclude any erroneous data and to correct any obvious offsets in the acceleration data that were evident. For example, in each file the longitudinal acceleration signal was corrected to account for any offset that was evident when the vehicle was stationary (Figure 19). This was an important correction to ensure that measured values of peak and mean deceleration were as accurate as possible.

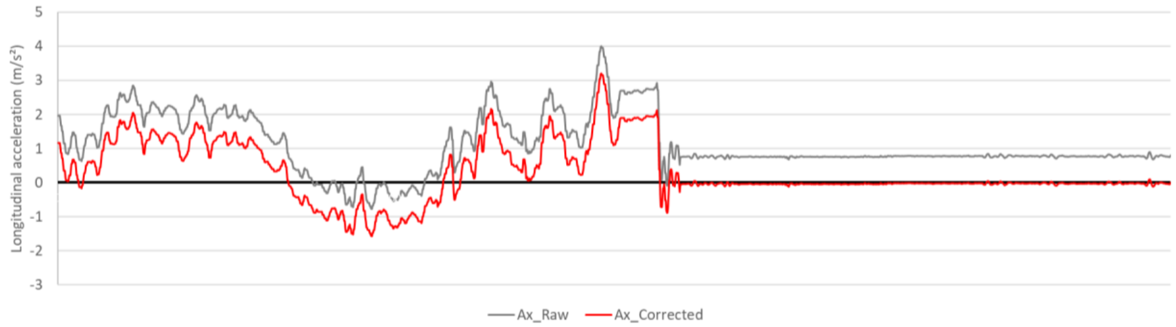


Figure 19: Example of offset evident in raw telematics data

Figure 20 below shows a short extract from one raw file covering approximately two minutes of driving. The signal from the throttle pedal (blue) was a graduated signal providing information about how far it was pressed by the driver. The signal from the brake pedal (grey), however, was a binary signal that simply indicated whether the pedal was pressed (to any level) or not, hence why it only switches between 0 and 100 on the chart.

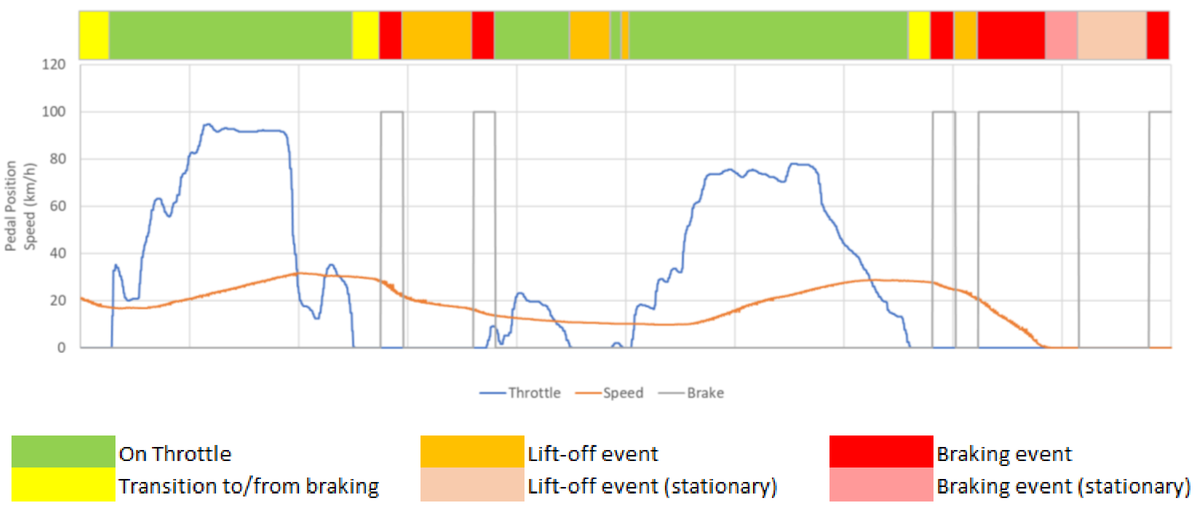


Figure 20: Example time history showing categorisation of pedal status

The analysis routines divided each raw file into one of five different driving states:

- On Throttle: Any time when only the accelerator pedal was pressed, and the brake pedal was released.
- Transition: Time when neither brake and throttle pedal were pressed but the driver was transitioning between the pedals, e.g., brake to throttle or throttle to brake.
- Lift-off: Time when neither pedal was pressed, and the driver was not transitioning between pedals, e.g., the driver changed from pressing the accelerator to releasing it before pressing it again.
- Brake event: Any time when the brake pedal was pressed.
- Stationary events: Either a lift-off or braking event when the vehicle was stationary, e.g., at traffic lights.

The lift-off events and braking events were selected as the ones of interest for this study. The start and end points of each event were used as boundaries for calculating the various metrics described in the following section.

Some minimal smoothing in the form of a 3-sample moving average, was applied to the longitudinal acceleration field in the raw file to provide a cleaner signal without overly distorting the peak values and rates of change observed. The signal was also smoothed with a moving average over a longer period of 1.6 seconds to approximate the level of filtering applied by Greenroad to the data set they provided, which was used for analysing differences between pre and post pandemic conditions (see section 6). This allowed a direct comparison of the two data sources.

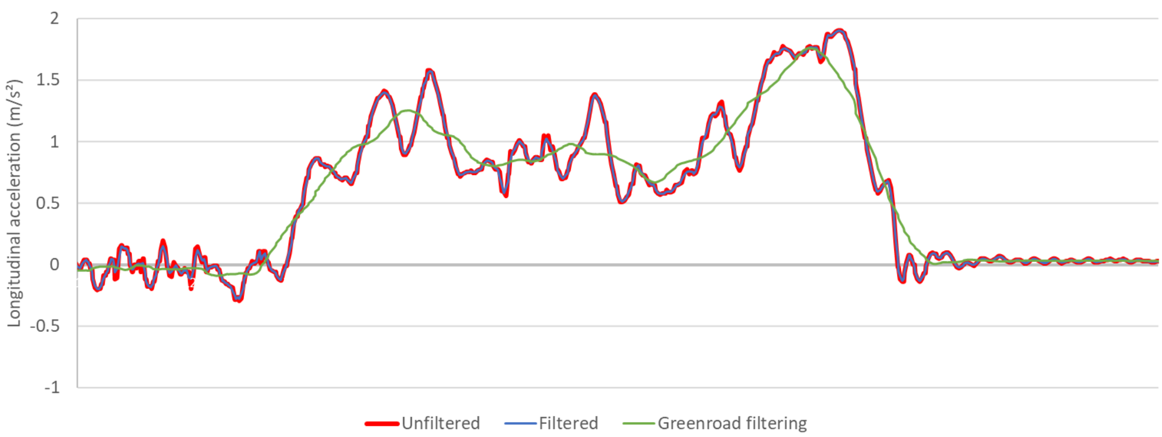


Figure 21: Example of the effect of smoothing of the data

4.2.2 Event analysis

For each braking and lift-off event the following metrics were calculated:

- Peak deceleration
- Mean deceleration
- Time to peak deceleration
- Peak Jerk
- Time to peak Jerk
- Start & end travel speed
- Distance travelled during event

An initial analysis of data captured during the first month of the trial was used to identify and implement some basic rules to exclude invalid data and improve the quality of remaining data set. These excluded cases when:

- The initial speed of the bus was < 5km/h
- The peak or mean deceleration was negative (the accelerometers were set up to record braking as a positive acceleration) or the vehicle's speed did not decrease (i.e., the bus was not slowing down, e.g. check braking on a slope)
- The duration of the event was less than 0.1 seconds.

4.3 Characterising normal braking behaviour of human drivers

Over 12 million deceleration events were recorded by the 50 buses in service during this project. Table 4 shows a breakdown of these events by the peak deceleration recorded during each event. It shows that 99% of all events had a peak deceleration of less than $3m/s^2$.

Table 4: Breakdown of deceleration events by peak deceleration

Peak deceleration (m/s^2)	Event Count	Proportion
0-1	5,968,521	49%
1-2	4,772,122	39%
2-3	1,446,222	12%
3-4	71,202	1%
4-5	3,179	0.03%
5-6	401	0.003%
6-7	82	0.0007%
7-8	59	0.0005%
8-9	36	0.0003%

The 50 buses travelled over 1.1million km (700,000 miles). Table 5 shows how frequently deceleration events for each level of peak deceleration occurred for every km travelled.

Table 5: Breakdown of the rate of deceleration events per km travelled

Peak deceleration (m/s²)	Count	Events per km	km between events
0-1	5,968,521	5.30	0.19
1-2	4,772,122	4.24	0.24
2-3	1,446,222	1.28	0.78
3-4	71,202	6.32E-02	15.8
4-5	3,179	2.82E-03	354.42
5-6	401	3.56E-04	2,809.75
6-7	82	7.28E-05	13,740.38
7-8	59	5.24E-05	19,096.80
8-9	36	3.20E-05	31,297.54

Figure 22 shows the number of events per km on a graph, noting that the y-axis is on a logarithmic scale so that there is an order of magnitude difference between each major gridline.

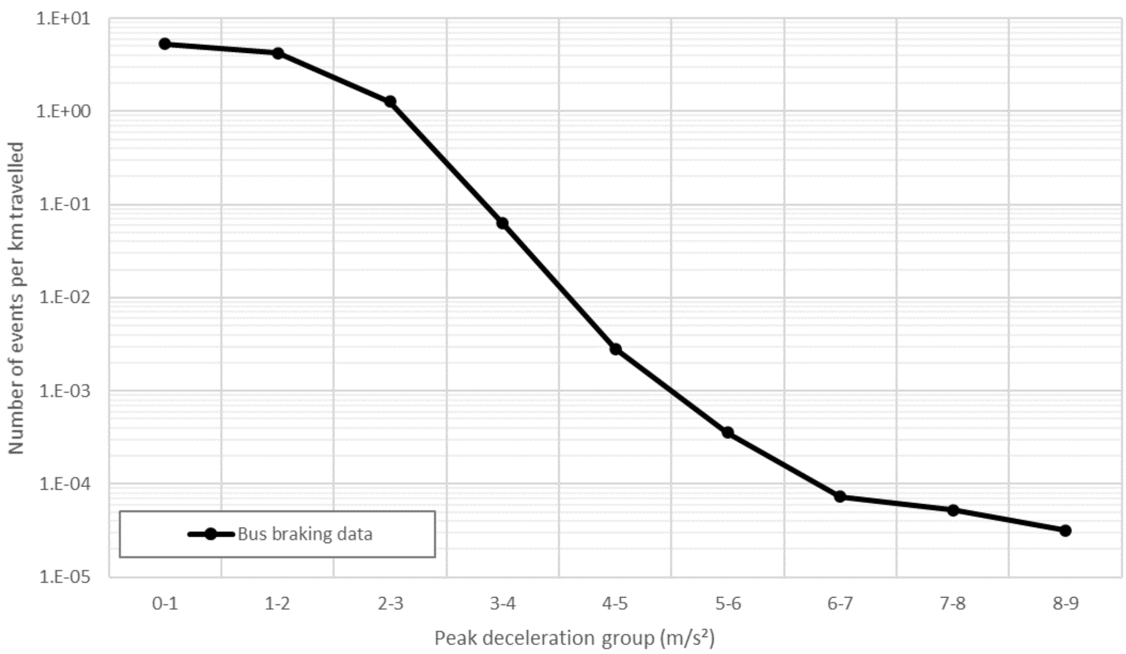


Figure 22: Chart showing deceleration events per km travelled by peak deceleration

Figure 22 shows the relative high frequency of events at low levels of deceleration, and also shows that, as the magnitude of deceleration increases, the frequency of events declines at a rate of approximately one order of magnitude per deceleration group. Above 6 m/s² the decline in frequency plateaus somewhat. Note that replicating this graph for each month of the study shows a high consistency of results.

Figure 23 shows this result compared to the original result of the Phase 1 BSS AEB analysis. In the original study, only low-level events were recorded during the short road trial and the extrapolation to higher rates of deceleration was based on a trendline which assumed that the rate at which the frequency of events declined remained constant for all deceleration groups.

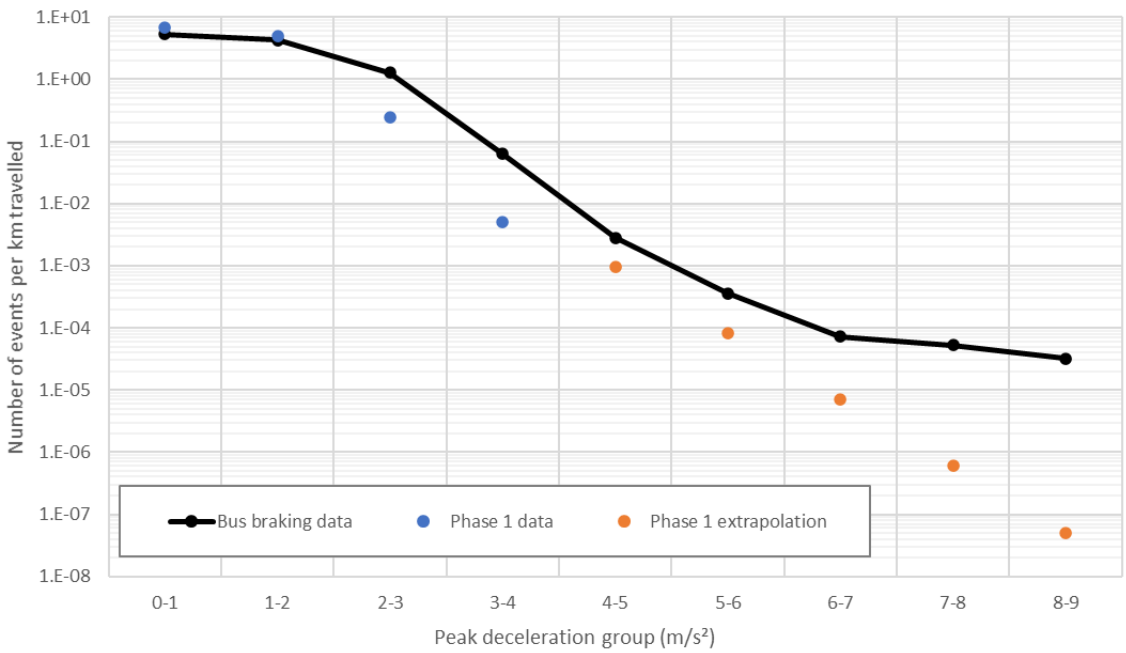


Figure 23: Comparison of deceleration events per km for this bus braking study and original Phase 1 study

This latest study has shown that deceleration events occur much more frequently than originally estimated from the previous short road trial, particularly at higher levels of deceleration. This suggests that, if all else stays the same, the number of casualties occurring in London as a consequence of medium to high levels of braking, occurred from a much larger number of total brake applications than previously thought. This will tend to produce a lower estimate of casualty risk per brake application.

4.3.1 Adjustment for empty buses

During the early phase of the data collection, a selection of heavy braking events (> 5.0 m/s²) were identified in the data and then CCTV footage of the incident was downloaded. This was initially done with the aim of validating and verifying that the results seen in the data corresponded to a genuine event, which they did.

However, a notable, but unexpected, finding was that of the 60 cases that were reviewed, only 10 cases (17%) had passengers on board the bus at the time of the incident. Some of these cases occurred when the driver was undertaking a brake test outside the depot at the start of their shift and others were on the public roads resulting from late braking at, for example, traffic lights and roundabouts. By definition, passenger injuries cannot occur during these events so there is an argument for excluding them from consideration.

On the assumption that this pattern was representative of all heavy braking incidents with a peak deceleration over 5.0 m/s², then the rate of heavy braking incidents per km travelled with passengers on board would be lower, as shown by the purple data points in Figure 24. The result still indicates that heavy braking events occur much more frequently than originally estimated in the Phase 1 study.

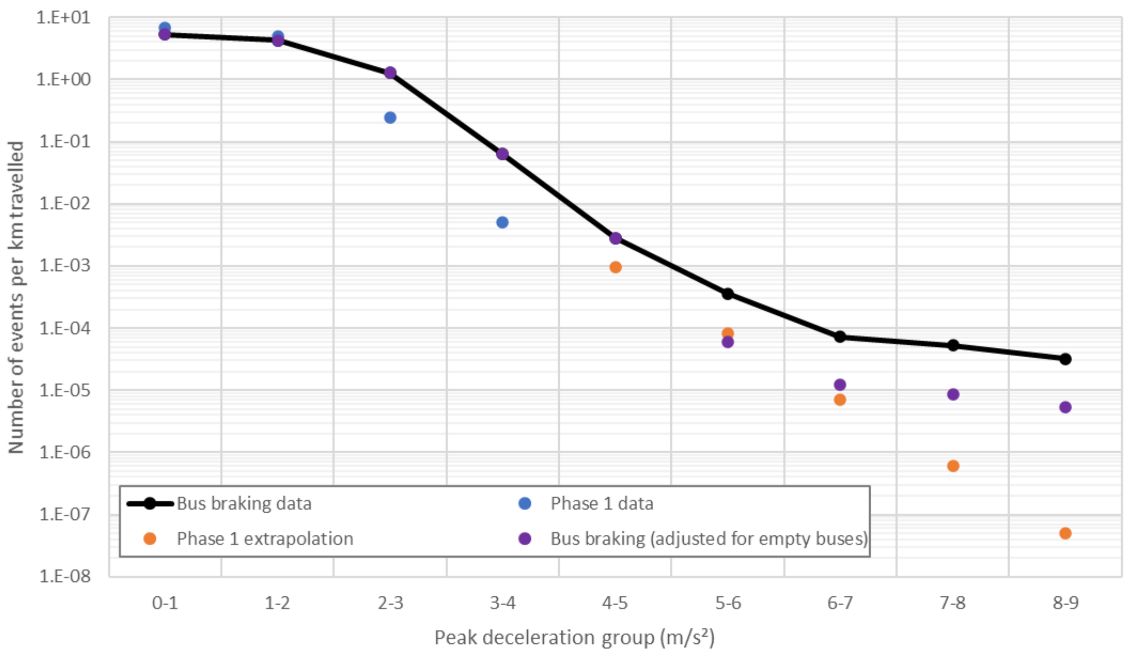


Figure 24: Deceleration events per km travelled by peak deceleration, including an adjustment for empty buses

4.4 Greenroad Telematics data

To further extend the data sets in this study, an additional source of data on the frequency of braking events was identified. Greenroad telematics provides solutions to several London bus operators and was able to compile historic data from its database. Because the data was historic, it could not be adapted to the specific requirements of the project. It was defined as per the specification of each operator, which did vary between operators in some respects. This led to a limitation that the lower levels of deceleration were not present (the system is set up to collect 'harsh' braking events for operators) and there were some complications with the classification of data at high accelerations varying between different operators.

The data was anonymised, so details of the specific routes was not available, but it did not overlap with the data gathered by 21st Century. The full sample covered almost 1 billion bus km over a period of 2009-2020. A subset of this covering 88 million bus km from 2018 to 2020 inclusive, was analysed on a weekly basis to allow comparison of pre and post pandemic results. Braking events were defined based only on the deceleration recorded by the vehicles on-board system, rather than the activation of the brake pedal.

Figure 25 shows a comparison of the Greenroad data set to the data captured during this project and the Phase 1 BSS project. The data shows that for events with a peak deceleration of up to 6m/s² a lower frequency of events was recorded. However, for the higher rates of deceleration (> 5m/s²) the frequency matched very closely to that recorded using the 21st Century data when it included an adjustment for empty buses.

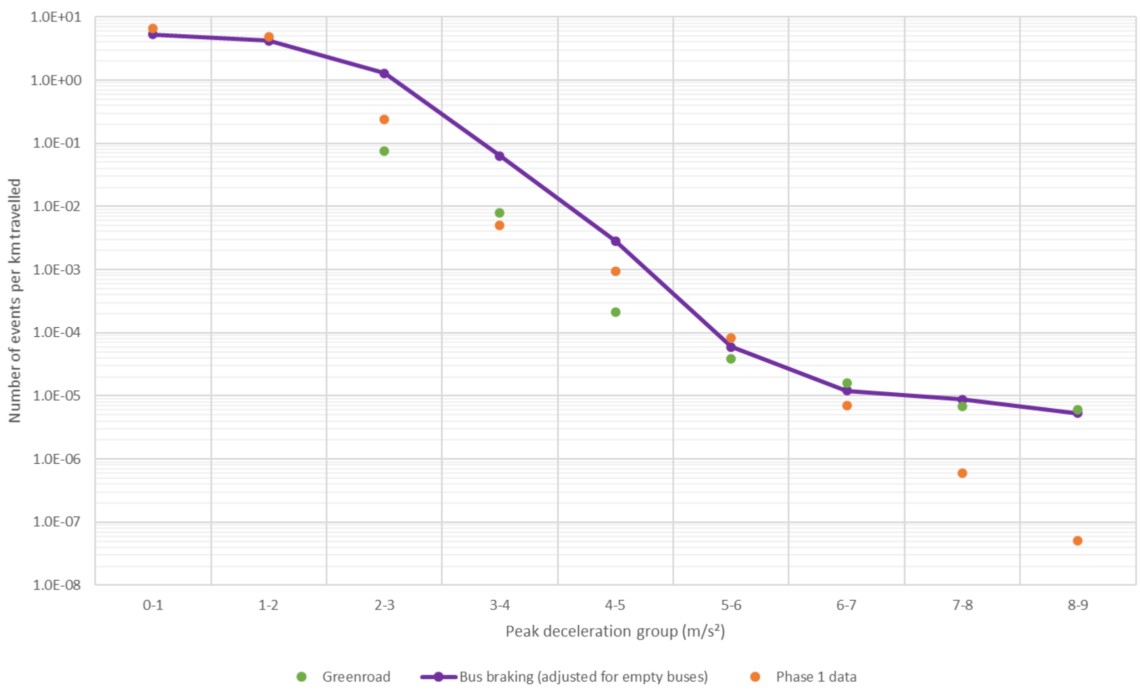


Figure 25: Deceleration events per km travelled by peak deceleration using Greenroad data and compared to bus braking data and Phase 1 data

A further comparison of the pre/post COVID results is presented in section 6 and analysis by drivetrain shown in section 7.3.

5 Updating predicted net effect of AEB on casualties

As part of the development of the predictive model developed for this project, the cost-benefit calculations from the earlier work (Knight *et al.*, 2019) were reproduced to provide a baseline for comparison with the new/updated data sources.

To provide continuity with the original BSS study, the calculations were based on STATS19 data covering the period 2006-2015, and bus occupancy levels, bus vehicle km and casualty valuations from 2017 were used. The analysis assumed all buses would be fitted with AEB with the same levels of effectiveness as reported in (Knight *et al.*, 2019). The monetised values are calculated based on 2016 DfT values.

That analysis was based on consideration of different concepts for the tuning of an AEB system 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, this is assumed to be 9 m/s^2 which is in line with the tests performed in the Phase 1 BSS study.
- **AEB$_{cap5}$**: AEB system is tuned to cap braking at a lower rate of deceleration (5 m/s^2), 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$_{cap7}$**: This approach is a middle ground between the above two scenarios with a maximum deceleration of 7 m/s^2. This 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.

5.1 Reproduction of Phase 1 results

The exact model used in phase 1 was recreated rather than simply re-used with different inputs, because it was intended that new elements (e.g. modelling of post pandemic scenarios) would be added and it was thought easier to redesign with those in mind from the start. The revised model was, therefore, first tested by assessing whether it would exactly reproduce the same outputs as reported by (Knight, et al., 2019) if given the same inputs.

In fact, this proved not to be the case, and slightly different numbers were obtained. The variation was traced to a minor error in the original model. The results shown in Table 6 below are the baseline figures produced based on the state of knowledge and the inputs available in 2018. However, as a consequence of the previous small error, they are slightly different to those published by (Knight, et al., 2019).

Table 6: Total annual net casualty effect of the original true positive and false positive analyses (Baseline position based on original inputs from (Knight *et al.*, 2019))

AEB_Performance	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	2.2	-	2.3	17.9	-	23.5	-89.4	-	15.5	-69.4	-	41.3
AEB$_{cap5}$ (5m/s²)	2.0	-	2.0	28.9	-	29.5	26.1	-	85.9	57.0	-	117.4
AEB$_{cap7}$ (7m/s²)	2.2	-	2.2	27.0	-	28.6	37.8	-	79.9	67.0	-	110.7

The difference in exact output compared to (Knight, et al., 2019) would not have materially affected the conclusions of that work, which remain identical. Table 6 shows that the AEB$_{max}$ variant was expected to prevent 2.2 to 2.3 fatalities and 17.9 to 23.5 serious casualties per year. However, the effect on the number of slight injuries was expected to range from an increase of 89.4 per year to a reduction of 15.5 per year as a consequence of the anticipated level of false positive events. The range of values for each category reflects the uncertainty that existed about the frequency of false positive events, so the calculations were made based on one false positive event occurring between once every 600,000km to once every 1,000,000km

Although the overall number of casualties was predicted to increase for the AEB$_{max}$ system if false positives occurred more frequently, applying the standard DfT economic values for the prevention of those casualties showed that all three performance levels offered a net monetised benefit (Table 7).

Table 7: Total annual net monetised casualty effect of the original true positive and false positive analyses. (Baseline position based on original inputs from (Knight *et al.*, 2019))

AEB_Variant	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	£4.0 m	-	£4.1 m	£3.7 m	-	£4.9 m	-£1.4 m	-	£0.2 m	£6.2 m	-	£9.3 m
AEB$_{cap5}$ (5m/s²)	£3.7 m	-	£3.7 m	£6.0 m	-	£6.1 m	£0.4 m	-	£1.4 m	£10.1 m	-	£11.2 m
AEB$_{cap7}$ (7m/s²)	£4.0 m	-	£4.0 m	£5.6 m	-	£5.9 m	£0.6 m	-	£1.3 m	£10.2 m	-	£11.2 m

Although the above figures were based on one false positive event occurring between once every 600,000km to once every 1,000,000km, the original analysis also considered the sensitivity of this result to a wider range of false positive rates, as shown in Figure 26.

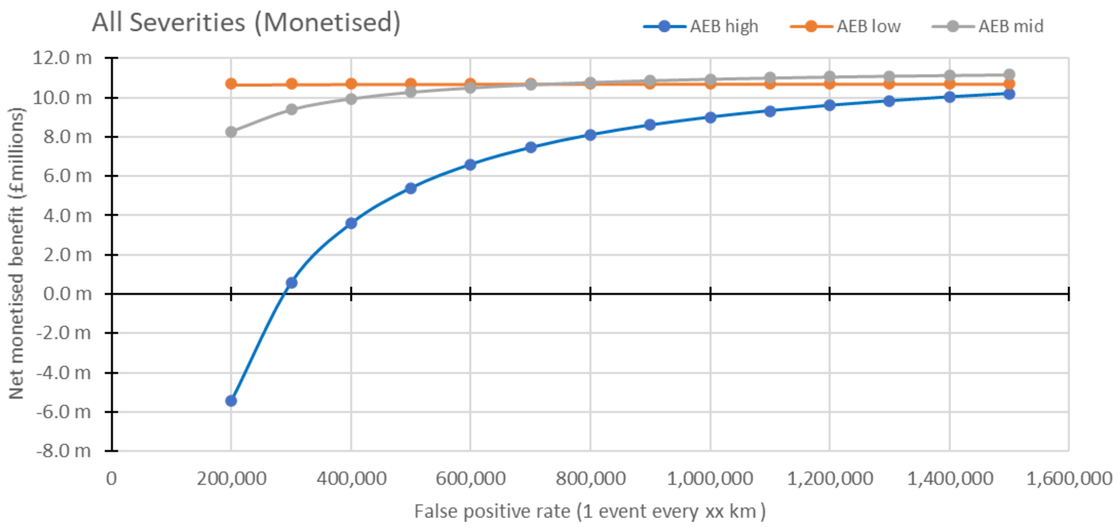


Figure 26: The effect of false positive rate on the annual net monetised benefit of each candidate AEB system (central prediction) (Baseline position updated from (Knight *et al.*, 2019))

This showed that capping the peak deceleration to 5m/s² or 7m/s² meant that the net effect was relatively insensitive to the false positive rate. However, a system that peaks at 9 m/s² was found to be much more sensitive to the false positive rate.

5.2 Updated for frequency of bus occupant casualties (CCTV analysis)

The additional CCTV cases that were reviewed as part of this study have provided greater confidence in relationships to define the proportion of occupants injured under braking and how those casualties are distributed based on the peak deceleration experienced.

The updated relationships, shown earlier in Figure 15 and Figure 17, are both broadly similar to those from the original Phase 1 study. Therefore, it is unsurprising that the additional CCTV cases have only had a minor effect on the overall cost benefit analysis.

Table 8 and Table 9 show that the net change in the number of casualties is less than 11 and that the net change in monetised effect is less than £0.3 million. The sensitivity of this result to a wider range of false positive rates is again shown in Figure 27.

Table 8: Total annual net effect of the original true positive and false positive analyses (Using updated data from CCTV analysis)

AEB_Performance	Fatal			Serious			Slight			Total		
AEB_{max} (9m/s²)	2.2	-	2.3	18.7	-	24.0	-79.4	-	20.0	-58.5	-	46.3
AEB_{cap5} (5m/s²)	2.0	-	2.0	28.9	-	29.5	24.2	-	84.9	55.2	-	116.5
AEB_{cap7} (7m/s²)	2.2	-	2.2	27.7	-	29.0	45.8	-	83.4	75.6	-	114.6

Table 9: Total annual net monetised casualty effect of the original true positive and false positive analyses. (Using updated data from CCTV analysis)

AEB_Variant	Fatal	Serious	Slight	Total
AEB$_{max}$ (9m/s²)	£4.0 m - £4.2 m	£3.9 m - £5.0 m	-£1.3 m - £0.3 m	£6.6 m - £9.5 m
AEB$_{cap5}$ (5m/s²)	£3.7 m - £3.7 m	£6.0 m - £6.1 m	£0.4 m - £1.4 m	£10.1 m - £11.1 m
AEB$_{cap7}$ (7m/s²)	£4.0 m - £4.0 m	£5.7 m - £6.0 m	£0.7 m - £1.3 m	£10.4 m - £11.3 m

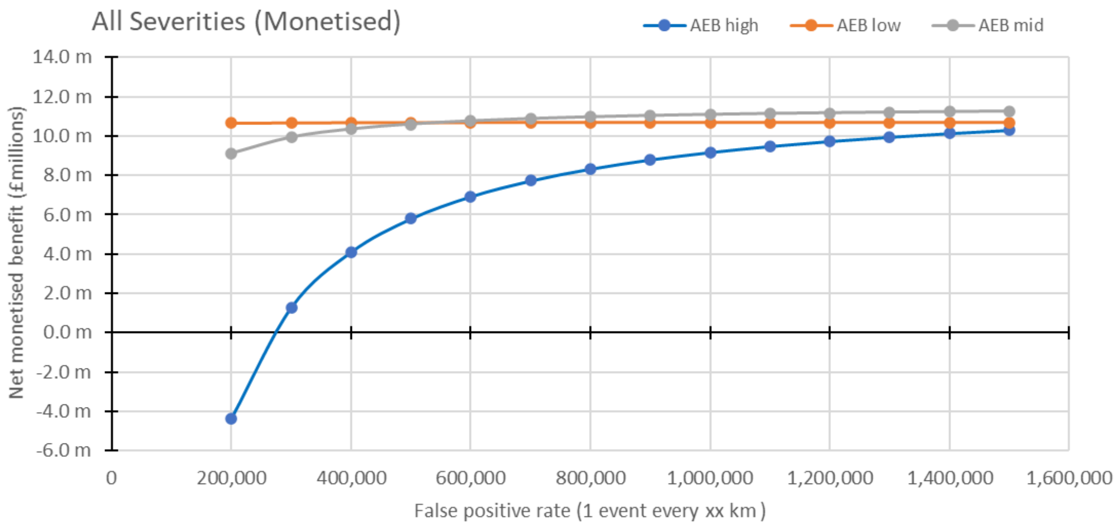


Figure 27: The effect of false positive rate on the annual net monetised benefit of each candidate AEB system (central prediction) (Using updated data from CCTV analysis)

5.3 Updated for frequency of brake applications in service (telematics)

The telematics data captured during this project has greatly expanded the amount of data available to quantify the frequency of braking events by the peak deceleration experienced. The analysis presented in section 4 also showed that, even if the figures are adjusted to exclude a proportion of events that occur when the bus is empty, heavy braking events occur much more frequently than estimated by the original study. This has had a profound effect on the cost benefit analysis as shown in Table 10, Table 11 and Figure 28 below.

All three AEB variants considered are largely insensitive to the false positive rate achieved with only a minor reduction in benefits when false positives occur most frequently. The maximum deceleration strategy (AEB$_{max}$) is most beneficial at all evaluated false positive rates.

Table 10: Total annual net effect of the original true positive and false positive analyses (Using updated data from telematics analysis and adjusted for empty buses)

AEB_Performance	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	2.4	-	2.4	30.5	-	31.1	71.0	-	111.7	103.9	-	145.2
AEB$_{cap5}$ (5m/s²)	2.0	-	2.0	28.9	-	29.5	26.1	-	85.9	57.0	-	117.4
AEB$_{cap7}$ (7m/s²)	2.2	-	2.2	28.1	-	29.3	51.3	-	88.0	81.6	-	119.4

Table 11: Total annual net monetised casualty effect of the original true positive and false positive analyses. (Using updated data from telematics analysis and adjusted for empty buses)

AEB_Variant	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	£4.4 m	-	£4.4 m	£6.3 m	-	£6.4 m	£1.1 m	-	£1.8 m	£11.8 m	-	£12.6 m
AEB$_{cap5}$ (5m/s²)	£3.7 m	-	£3.7 m	£6.0 m	-	£6.1 m	£0.4 m	-	£1.4 m	£10.1 m	-	£11.2 m
AEB$_{cap7}$ (7m/s²)	£4.0 m	-	£4.0 m	£5.8 m	-	£6.1 m	£0.8 m	-	£1.4 m	£10.6 m	-	£11.5 m

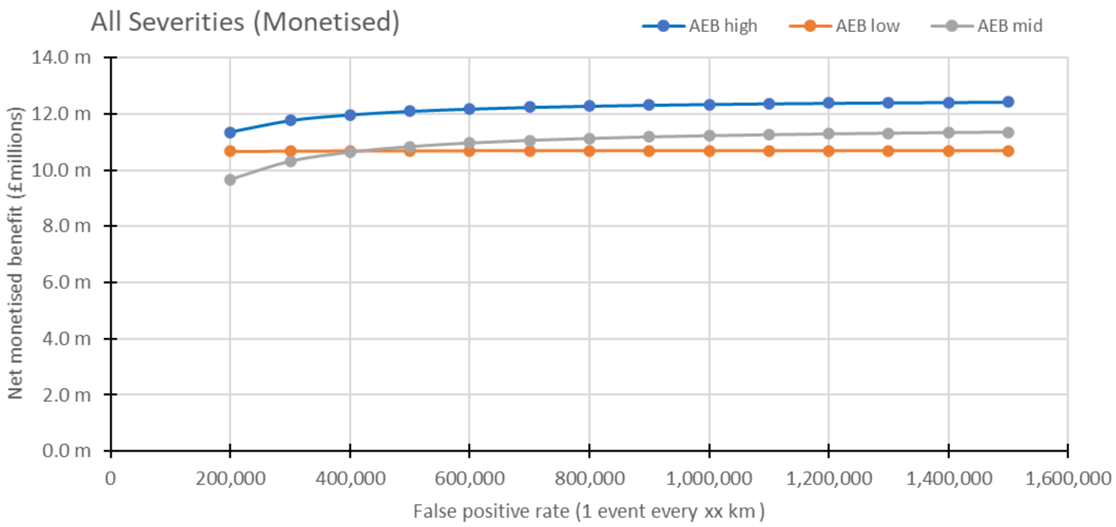


Figure 28: The effect of false positive rate on the annual net monetised benefit of each candidate AEB system (central prediction) (Using updated data from telematics analysis and adjusted for empty buses)

The naturalistic driving data recorded in this study showed that deceleration events (especially those at high levels of deceleration) are far more frequent than estimated by (Knight *et al.*, 2019). Although the chart shown in Figure 29 suggests that the trends are not too far apart it must be remembered that the vertical scale is a logarithmic scale and so each major interval represents a difference of one order of magnitude. For example, at the highest level of deceleration (8 – 9 m/s²) the Phase 1 data (orange data points) suggested that a braking event at this level would occur once every 19 million km. When applied to the whole London bus fleet this equates to just around 26 events each year. In comparison the latest data (black) suggests such an event would occur once every 40,000km, equivalent to approximately 475 events per year. This is an almost twenty-fold increase in frequency.

Even when accounting for the empty bus running, the heaviest braking events would still occur once every 245,000 km, or 80 times per year (more than a three-fold increase from the original study).

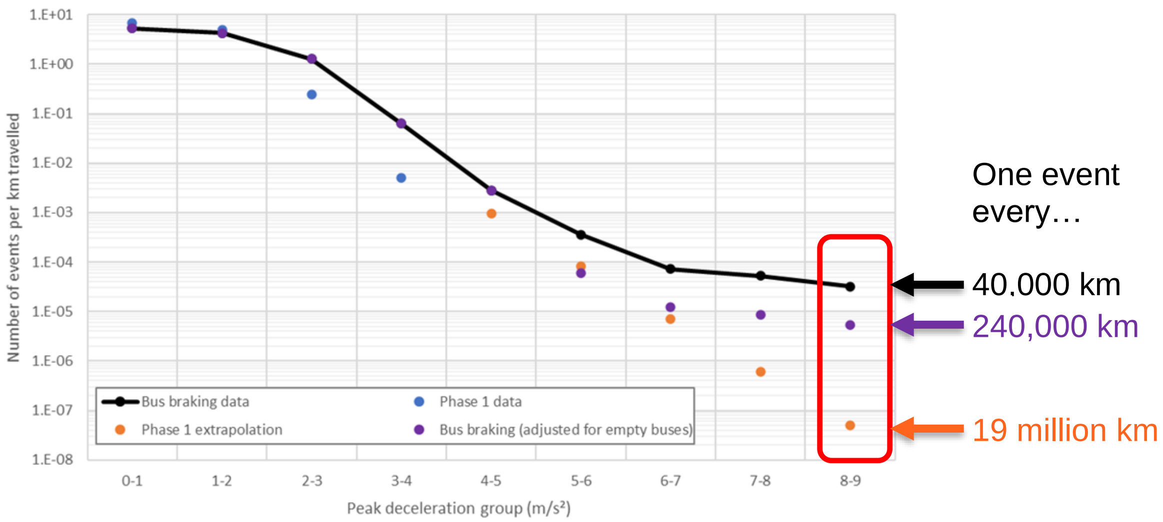


Figure 29: Deceleration events per km travelled by peak deceleration illustrating order of magnitude difference between data sets

Because the estimated number of high deceleration brake events has increased when using the new data set, but the overall number of casualties per year remains unchanged, this has the effect of reducing the number of casualties per brake event, thus reducing the negative effect if a false positive event were to occur, resulting in a vastly improved net benefit.

5.4 Combined result

The previous sections show the effect from expanding and updating the data on the frequency of bus occupant casualties (CCTV analysis) and the frequency of braking events (telematics) individually and using data from the original Phase 1 study for the aspect not under consideration.

Table 12, Figure 30, Table 13 and Figure 31 below, show the effect of updating both these aspects in combination. It is clear that the change in the frequency of braking events in normal service dominates the overall result and strongly suggests that the fitment of AEB to London buses would have an overall positive effect in reducing the number of casualties.

Table 12: Total annual net effect of the original true positive and false positive analyses (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

AEB_Performance	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	2.4	-	2.4	30.6	-	31.1	71.3	-	110.5	104.3	-	144.0
AEB$_{cap5}$ (5m/s²)	2.0	-	2.0	28.9	-	29.5	24.3	-	85.0	55.2	-	116.5
AEB$_{cap7}$ (7m/s²)	2.2	-	2.2	28.5	-	29.5	55.7	-	89.4	86.4	-	121.0

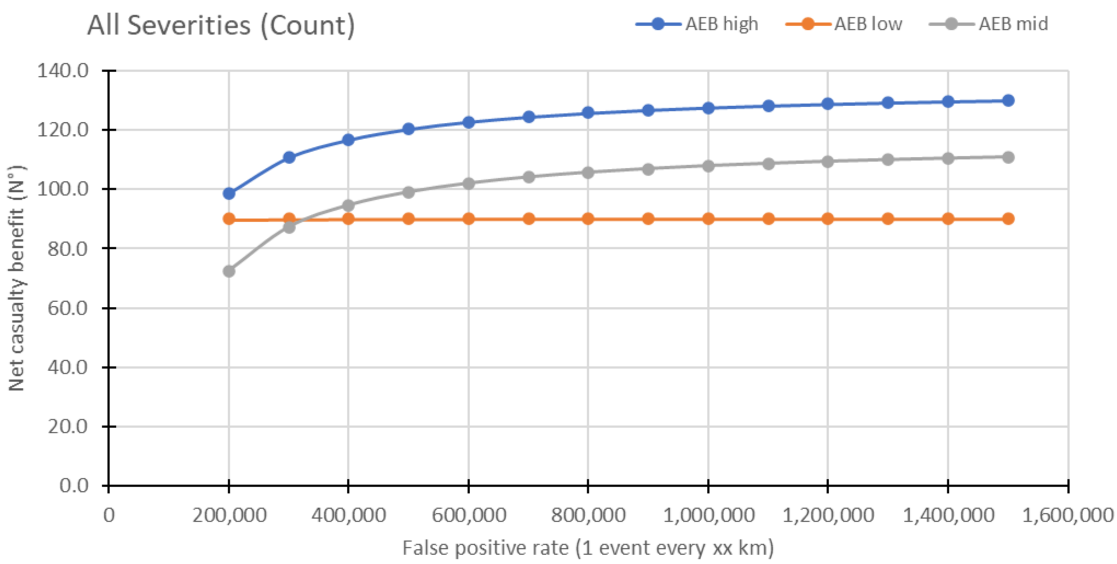


Figure 30: The effect of false positive rate on the annual net casualty benefit of each candidate AEB system (central prediction) (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

Table 13: Total annual net monetised casualty effect of the original true positive and false positive analyses. (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

AEB_Variant	Fatal			Serious			Slight			Total		
AEB$_{max}$ (9m/s²)	£4.4 m	-	£4.4 m	£6.3 m	-	£6.4 m	£1.1 m	-	£1.8 m	£11.9 m	-	£12.6 m
AEB$_{cap5}$ (5m/s²)	£3.7 m	-	£3.7 m	£6.0 m	-	£6.1 m	£0.4 m	-	£1.4 m	£10.1 m	-	£11.1 m
AEB$_{cap7}$ (7m/s²)	£4.0 m	-	£4.0 m	£5.9 m	-	£6.1 m	£0.9 m	-	£1.4 m	£10.8 m	-	£11.6 m

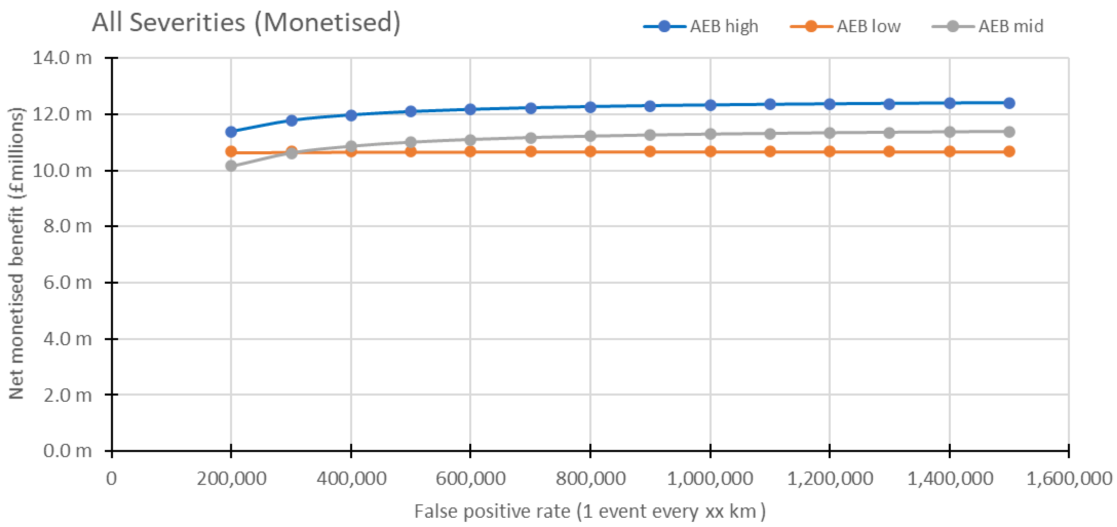


Figure 31: The effect of false positive rate on the annual net monetised benefit of each candidate AEB system (central prediction) (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

Figure 32, Figure 33 and Figure 34, show a further breakdown of the annual net monetised benefit of each candidate AEB system by casualty severity. It reiterates that although the greatest number of casualties are slight injuries, the greatest monetised benefit comes from the prevention and mitigation of fatal and serious casualties.

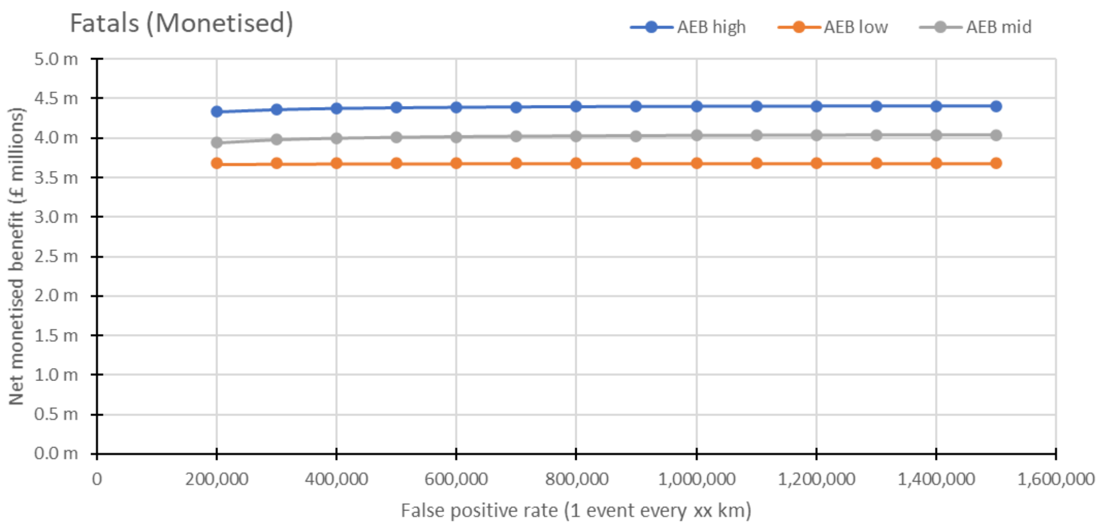


Figure 32: The effect of false positive rate on the annual net monetised benefit of each candidate AEB system (central prediction) for fatal casualties only (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

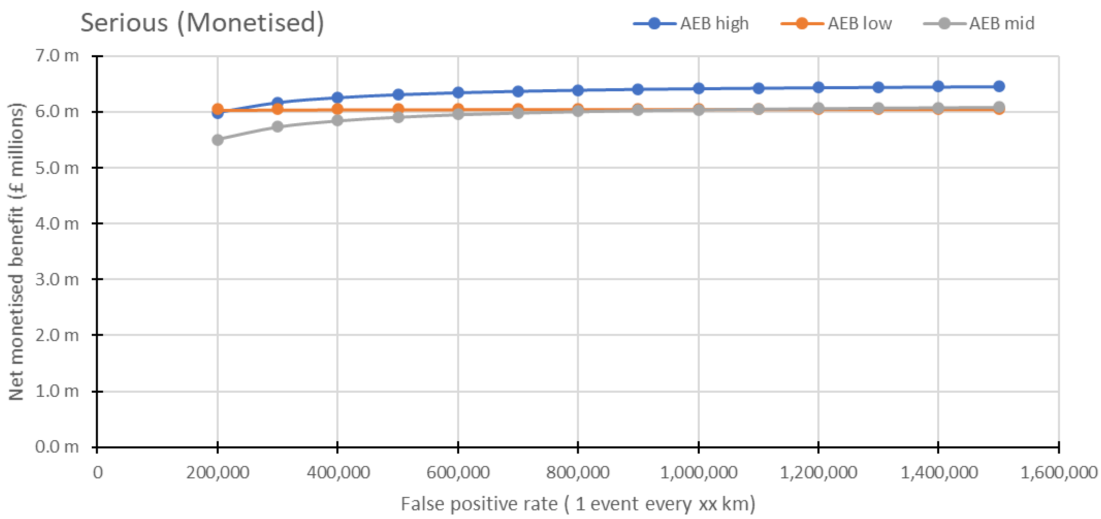


Figure 33: The effect of false positive rate on the annual net monetised benefit of each candidate AEB system (central prediction) for serious casualties only (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

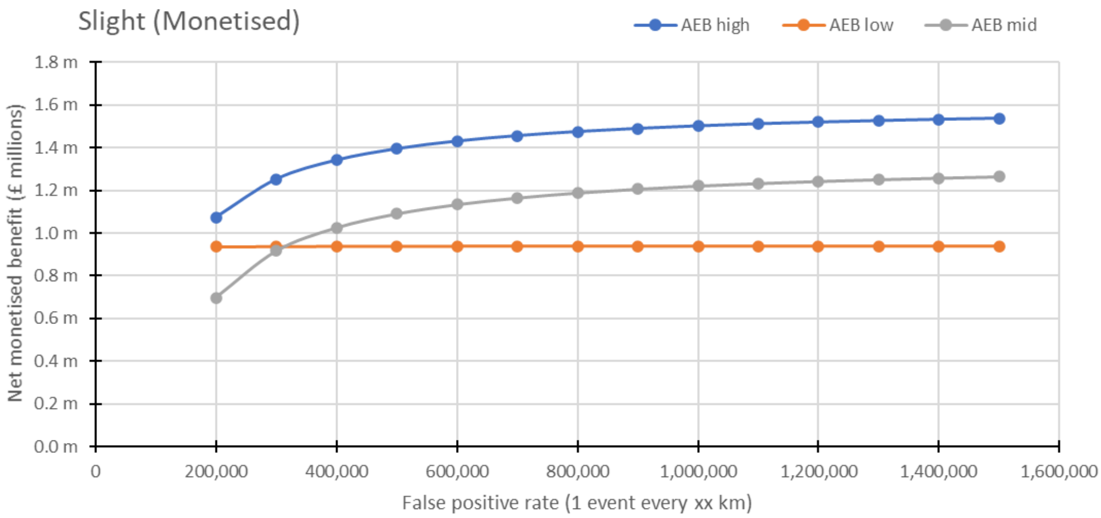


Figure 34: The effect of false positive rate on the annual net monetised benefit of each candidate AEB system (central prediction) for slight casualties only (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

6 Pre/post pandemic effects

All of the work undertaken by (Knight *et al.*, 2019) was completed prior to the start of the COVID-19 pandemic in 2020 and all of the work undertaken in this bus braking project has been completed in the period shortly after most restrictions began to ease in early 2021.

Therefore, it is important to consider whether the findings and conclusions from each study remain comparable and relevant to TfL going forward. This section provides an overview of how bus demand and incidents changed over the course of the pandemic. Data from a separate telematics supplier has also been analysed to consider if the frequency of braking events has changed over time.

6.1 Bus demand and the pandemic

TfL's Travel in London report (Transport for London, 2020) highlighted that immediately after the start of the first COVID-19 lockdown, bus demand fell to 14% of normal followed by a slow recovery, to approximately 55% of normal by early October 2020 (Figure 35). Supplementary data from TfL's bus safety team has shown that the slow recovery has continued reaching 70%-80% by September 2021.

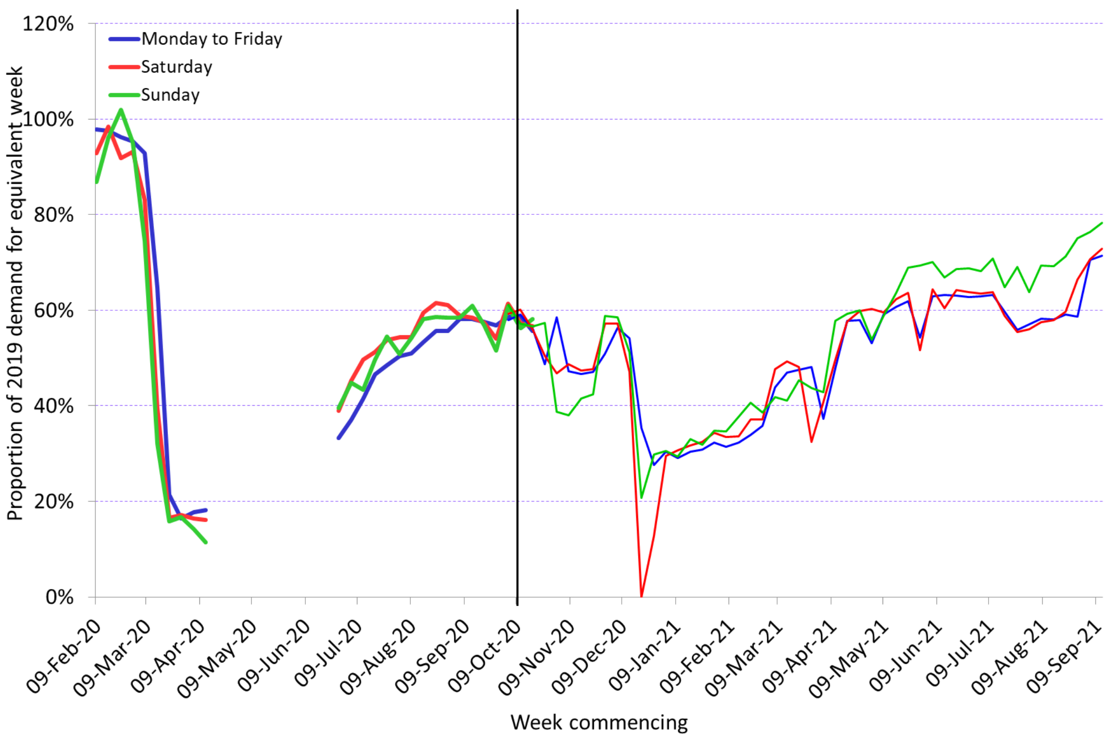


Figure 35: Bus demand by day of week, 2020 vs 2019
Source: (Transport for London, 2020) & TfL Bus Safety Team

TfL's bus safety statistics dashboard also shows how the number of reported collisions fell during the early stages of the pandemic but by the middle of 2021 have returned to a level close to those seen during 2019 and before.

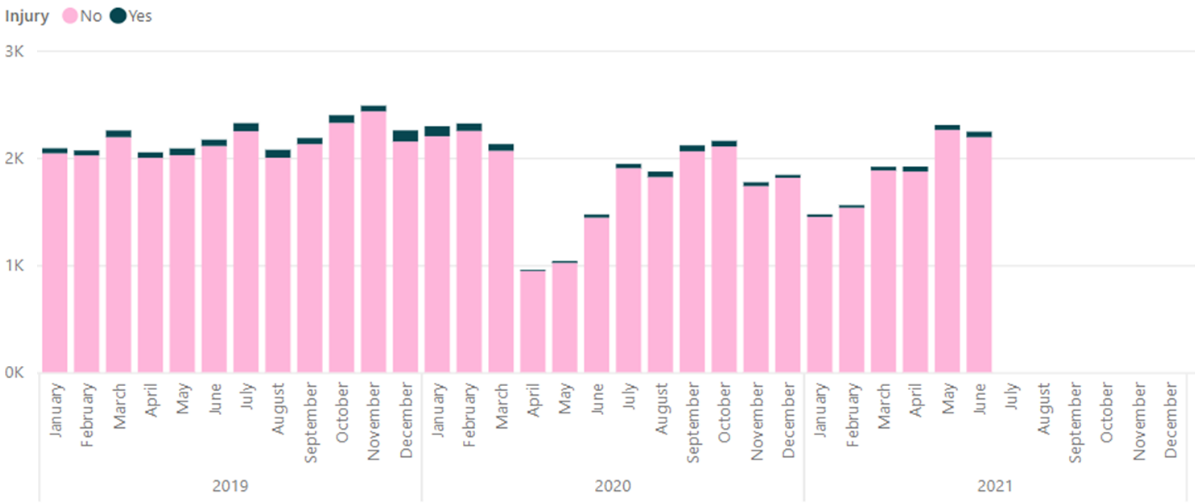


Figure 36: All reported bus collision incidents in London 2019 – 2021 Source: (Transport for London, 2021)

6.2 Braking events

A subset of the Greenroad telematics data covering a period of 1st January 2018 to 31st December 2020 was analysed on a weekly basis to consider the influence of the COVID-19 pandemic.

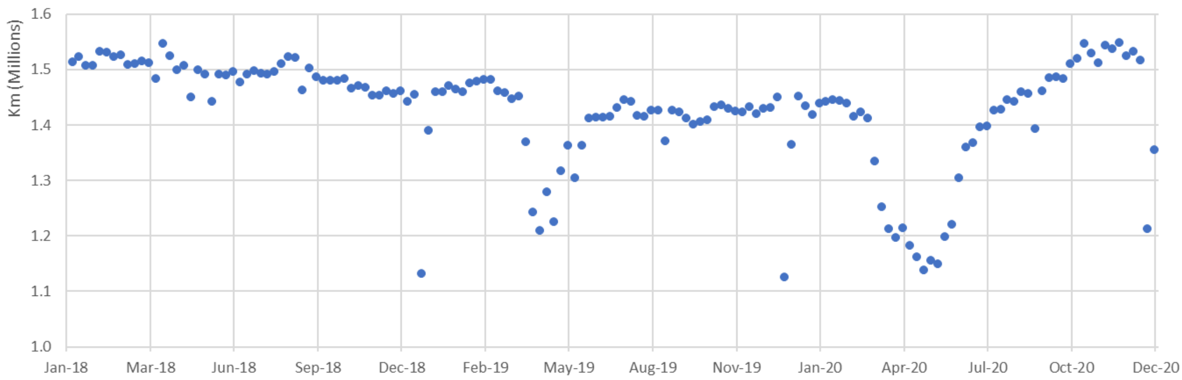


Figure 37: London Bus km over time for all buses active in Greenroad data for the entire period

It can be seen that two weeks at the end of each calendar year are always low, representing quiet Christmas periods. Other than that, the effect of the pandemic can clearly be seen with a substantial drop in bus km during the first lockdown and then an increase during recovery to a level in excess of that immediately pre pandemic. It is likely this is related to social distancing measures requiring more buses to cope with passenger demand, despite the overall lower level of passenger demand. The data also suggests (Figure 38) that the frequency of brake events per km driven has declined during the period, possibly related to overall traffic levels including other vehicles.

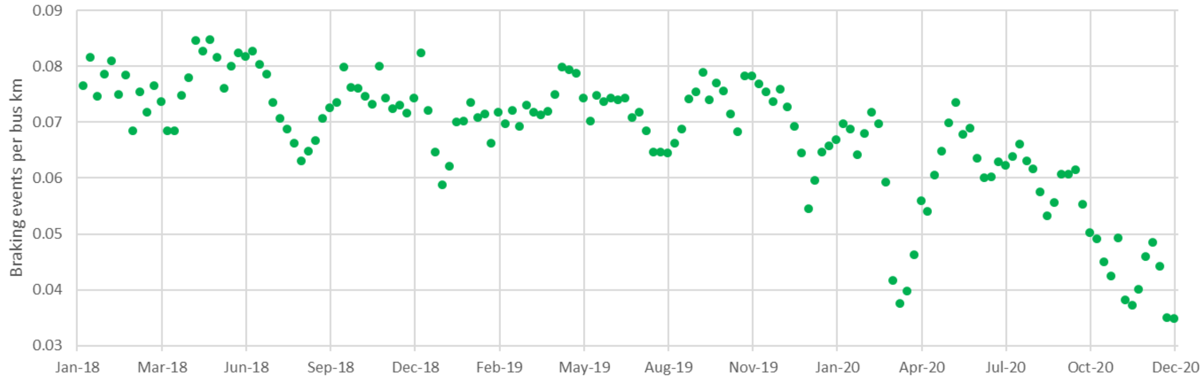


Figure 38: Brake events per bus km over time (2018-2020)

Analysis of the effect by deceleration level has suggested the proportional reduction in frequency may be slightly greater for higher deceleration levels than lower, though at the highest decelerations, ambiguities with the categorisation of events led to the exclusion of the data.

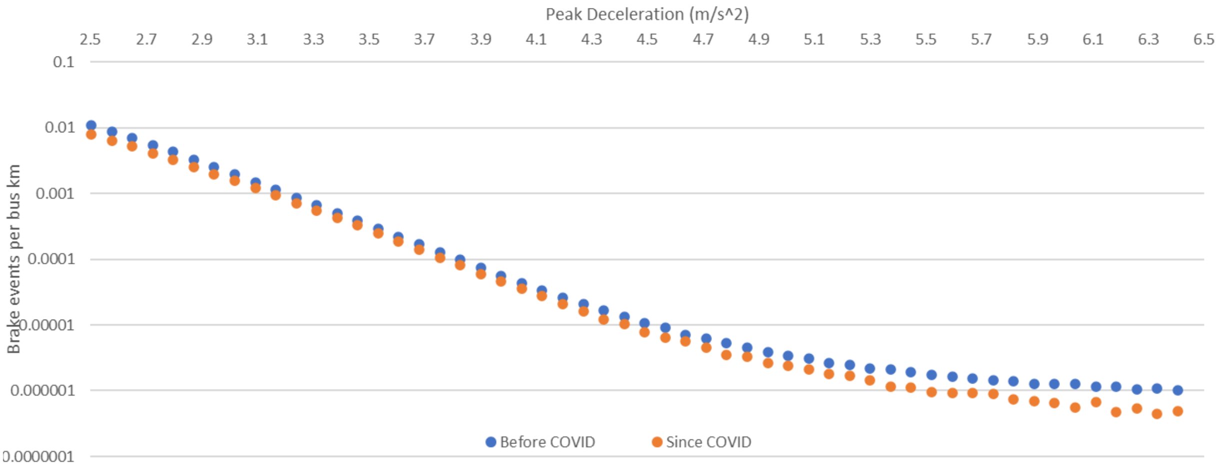


Figure 39: Brake events per bus km by peak deceleration pre and post March 2020

6.3 TfL's future scenarios

In response to the impact of COVID-19 on patterns of travel and the economy, resulting in significant uncertainty about the long-term impact, TfL has undertaken scenario planning to help inform future decision making. TfL produced five plausible scenarios for the implications of COVID 19 on travel demand. They considered:

- how quickly the public health crisis dissipates and the speed and nature of economic recovery
- how working, shopping and leisure practices might change in the medium to longer term
- changes to London's place in the world and impacts on population/demographics and jobs

The five scenarios are shown below in Figure 40 and more details of each scenario is provided in TfL's Travel in London Report[4] (Transport for London, 2020).

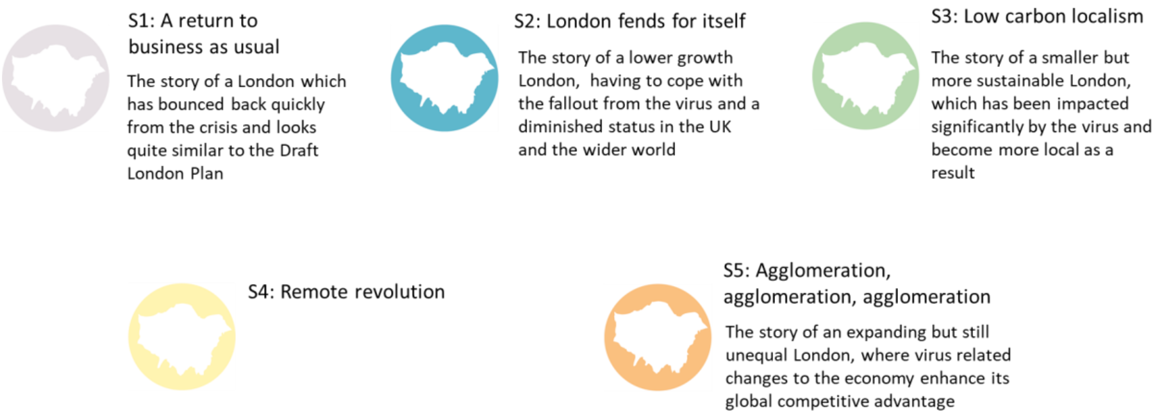


Figure 40: TfL's post-COVID-19 planning scenarios (Source: TfL's Travel in London Report)

Each scenario assumed a change in travel demand for a range of modes in 2030 compared to baseline figures reported for 2016 in TfL's Travel in London report (Transport for London, 2020). For example, Figure 41 shows that bus travel was predicted to decline in Scenario 2 (London fends for itself) and Scenario 4 (Remote revolution), to increase in Scenario 3 (Low carbon localism) and Scenario 5 (Agglomeration, agglomeration, agglomeration) and to remain similar to current levels in Scenario 1 (Business as usual).

[4] https://content.tfl.gov.uk/travel-in-london-report-13.pdf

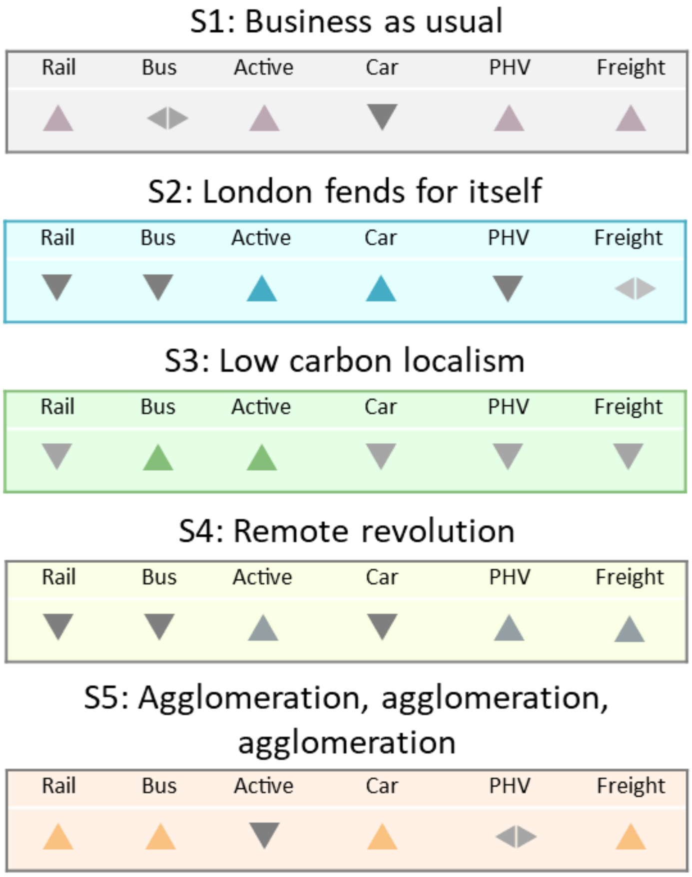


Figure 41: Predicted change in travel trends for each of TfL's post-COVID-19 planning scenarios

Using the estimated daily average number of trips (millions) in Greater London reported by TfL and combining that with the estimated change in demand for each travel mode, a future estimated daily average number of trips was calculated for each scenario and mode. These are summarised in Table 14 below. The table also shows combined number of daily trips for different incident types. For example, the combined number of trips for a bus v car incident is the sum of the daily bus trips and the daily car trips. This accounts for the fact that in some scenarios one mode was predicted to increase whereas the other was predicted to decline.

Table 14: Estimated daily trips (millions) by travel mode, individually and combined for different incident configurations

Estimated daily average number of trips (millions) in Greater London

Scenario\ Travel Mode	Bus	Car	Cyclist	Pedestrian
Current	3.8	9.8	0.6	6.5
S1: Business as usual	4.05	8.88	1.25	7.73
S2: London fends for itself	2.78	10.34	0.66	6.88
S3: Low carbon localism	4.50	9.90	1.37	7.69
S4: Remote revolution	3.12	8.85	0.64	7.17
S5: Agglomeration x3	5.53	8.71	1.35	8.60

Combined daily trips

Scenario\ Travel Mode	Bus occ casualties	Bus v car incidents	Bus v cyclist incidents	Bus v ped incidents
Current	3.80	13.60	4.40	10.30
S1: Business as usual	4.05	12.93	5.30	11.78
S2: London fends for itself	2.78	13.12	3.44	9.66
S3: Low carbon localism	4.50	14.40	5.87	12.19
S4: Remote revolution	3.12	11.97	3.77	10.29
S5: Agglomeration x3	5.53	14.24	6.87	14.13

For all other things being equal it was assumed that an increase/decrease in travel demand would equate to a proportional increase or decrease to the target populations[5] and relevant casualty[6] numbers used to estimate the net casualty effect of fitting AEB to London's buses.

For example, the baseline data estimated a combined 13.6 million daily trips by buses and cars and for Scenario 3 (Low carbon localism) the number of trips was estimated to be 14.4 million. This represents a 5.9% increase and so the target population and relevant casualty numbers were multiplied by this ratio to produce the updated numbers. This method was applied to each of the scenarios, with the effect of increasing/decreasing the net casualty effect from fitting AEB to London's buses.

Figure 42 and Figure 43 shows the comparison of the net casualty and monetised benefit each post-pandemic scenario compared to a baseline based on the AEB_{max} variant with the updated data on the frequency of bus occupant casualties (CCTV analysis) and the frequency of braking events (telematics), as shown by the blue line in Figure 31.

It can be seen that in most scenarios of post pandemic travel in London, the case for AEB further improves; only in "London fends for itself (S2)" or "remote revolution (S4)" does it worsen, and this is a relatively small reduction compared to the baseline result.

[5] Target population is defined as the total number of casualties that occur in London each year. e.g., for bus v car incidents, this is all bus or car occupants involved in bus v car incidents.

[6] Relevant casualties are a subset of the target population that could potentially be influenced by the fitment of AEB on buses.

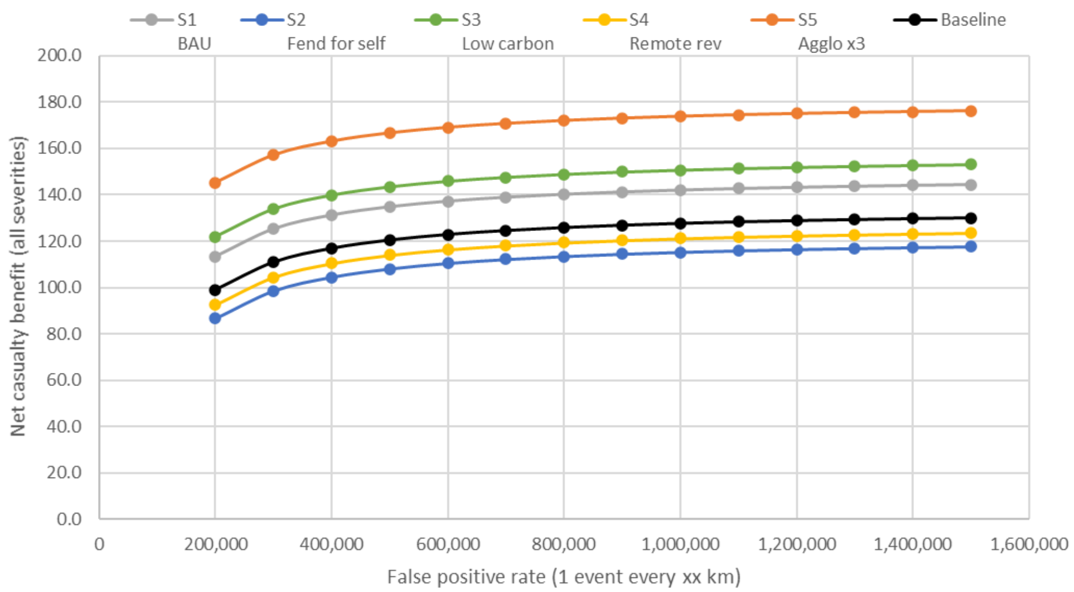


Figure 42: Comparison of the net casualty effect of the AEB$_{max}$ variant (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

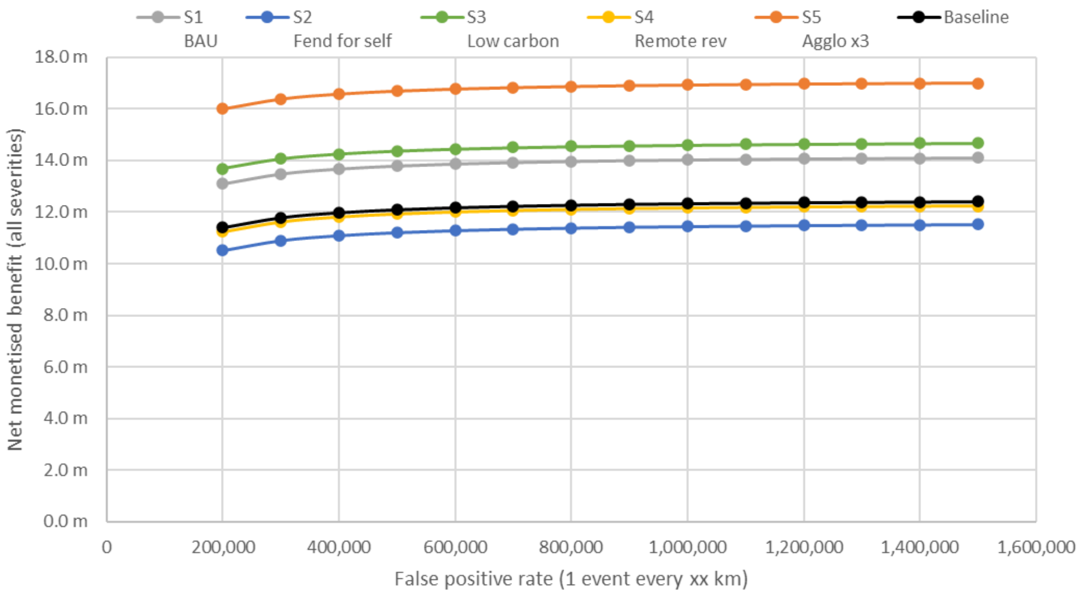


Figure 43: Comparison of the net monetised effect of the AEB$_{max}$ variant (Using updated data from CCTV and telematics analysis and adjusted for empty buses)

Since the start of the COVID pandemic bus occupancy numbers have fallen by 61%[7] but bus occupant injuries from slips, trips and falls have only fallen by about 34% in the same period. This is despite the likelihood of more occupants now being seated. It is possible that travel speed might be a factor. Less traffic on London's roads and fewer passengers to stop for could means higher travel speeds and more need for heavy braking. People may also be more reluctant to hold on or touch perceived "unclean" handrails which are fitted to help prevent falls. Further investigation of such factors would be needed to understand this more.

Analysis in this project has shown that post-pandemic reductions to the number of bus occupants and STF casualties, along with fewer bus km travelled each year give a small improvement to the overall net effect (well within the range of post-pandemic scenarios presented above). The improvement is a result of a reduction in the number of bus occupant casualties arising from false positives.

[7] DfT average bus occupancy data (BUS0304) 2018/19 v 2020/21

7 Additional considerations

7.1 Informing consideration of ethical effects

The report commissioned by the European Commission into the ethics of Connected and Automated Vehicles (CAVs) provides a useful reference when considering the ethical aspects of AEB (Bonnefon *et al.*, 2020). AEB is not a fully automated CAV system, and is only meant to be a driver support system that intervenes in the event of an emergency, rather than taking over the full driving task. However the principles are still relevant and important to consider, in particular:

- Recommendation 1: Ensure that CAVs reduce physical harm to persons
- Recommendation 5: Redress inequalities in vulnerability among road users

The net casualty benefit of fitting AEB to London's buses is comprised of two main components:

- Casualty benefit in true positive situations
- Casualty disbenefit in false positive situations

(Knight *et al.*, 2019) expected that the benefit in true positive situations was primarily from reducing pedestrian fatalities, while the disbenefit was predominantly to bus passengers. However, this wasn't explicitly quantified by road user group. A concern raised at a separate TfL workshop considering the ethics of a system that risked causing injury to bus passengers raised the concern that this may systemically advantage one demographic over another. That is pedestrians may commonly be younger and fitter than bus passengers that may more commonly be older or with mobility impairments. Thus, analysis of the demographics of the casualties involved was undertaken. It is also worth noting here that the ethics recommendation 5 (Bonnefon *et al.*, 2020) about redressing inequality among VRUs was focussed on the road users type (pedestrian, cyclist, driver), whereas in this report we are taking the analysis as step further by considering the age and gender demographics.

The benefits associated with True Positive situations can be considered fixed in the modelling because they do not change as the false positive rate of the AEB system changes. Figure 44 shows that the greatest casualty benefit is expected to affect pedestrians. As well as causing risks to bus occupants because of false positive activations, (Knight *et al.*, 2019) found that AEB would on average slightly increase the deceleration experienced during true positive brake applications. AEB cannot apply the brakes any harder than a human driver fully applying them. However, it was found that even in real pedestrian collisions, the brakes were often not fully applied to the maximum by the driver. In some of these cases it was found that AEB would have been applied earlier than the human did such that the collision could be avoided with a lower peak deceleration than the driver actually applied. In other cases, despite earlier intervention, heavier braking was still required to avoid collision. The net effect was a slight increase in the average.

The analysis of (Knight *et al.*, 2019) also found that there were benefits to bus occupants in terms of avoiding even higher decelerations that could occur because of collisions with cars, vans, trucks or other buses. However, this benefit to bus occupants from avoiding collisions with other vehicles was slightly outweighed by the increased risk from the increased deceleration. The net casualty reduction expected from true positive situations is shown in Figure 44 broken down by each road user group. Figures relate to the AEB_{max} variant and, although the absolute numbers change for the AEB_{cap5} and AEB_{cap7} variants, the overall pattern is the same. Positive values represent a casualty reduction, and negative values a casualty increase. The analysis is based on the new and updated data from CCTV and naturalistic driving studies in this report.

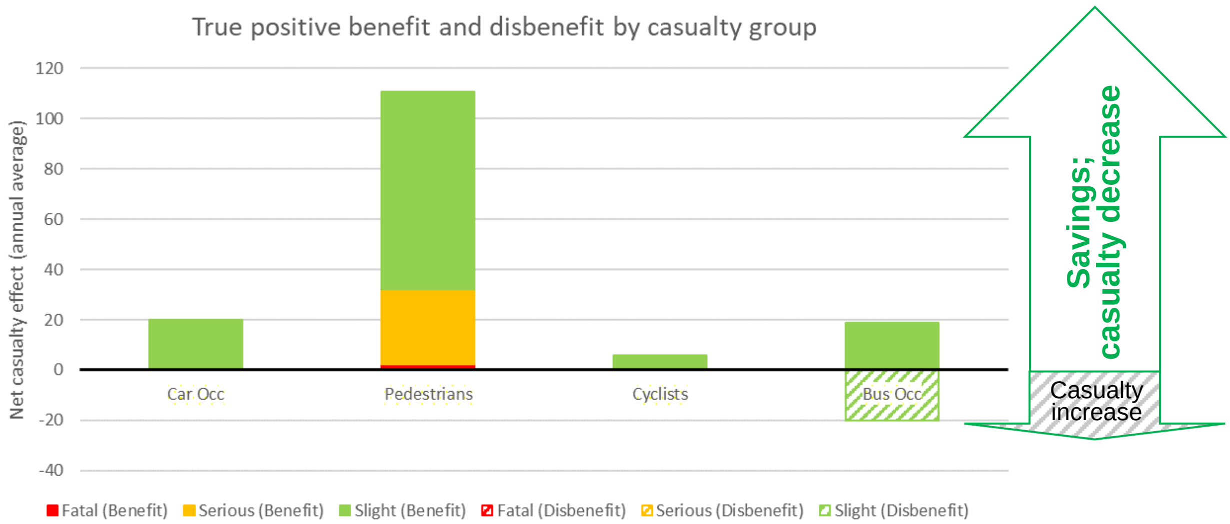


Figure 44: Average annual net casualty effect from true positive situations – AEB_{max} variant based on updated telematics and CCTV data

If a false positive occurs, then the bus occupants are at risk of injury from a braking event that should not have occurred had the AEB system functioned as intended. The more frequently that a false positive occurs, the greater the risk.

If bus occupants are considered in isolation, then the fixed effect of the true positive events shows a small overall disbenefit (blue line in Figure 45) that is completely insensitive to false positive rate. A further disbenefit from false positive events is shown by the purple line. The overall effect of AEB specifically on bus occupants is always negative, although a better false positive rate helps to mitigate this.

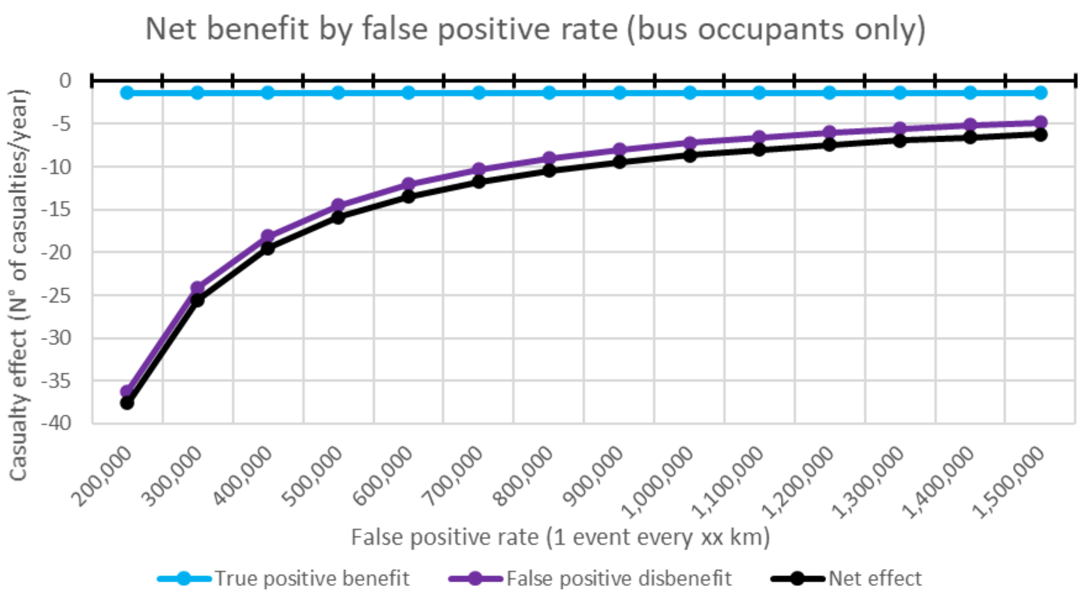


Figure 45: True positive, false positive and net casualty effect (bus occupants only) by false positive rate – AEB_{max}

For this AEB_{max} variant, the overall effect on bus occupants is always negative, albeit small when considered in comparison to the larger true positive benefit of preventing injures to pedestrians, cyclists and car occupants.

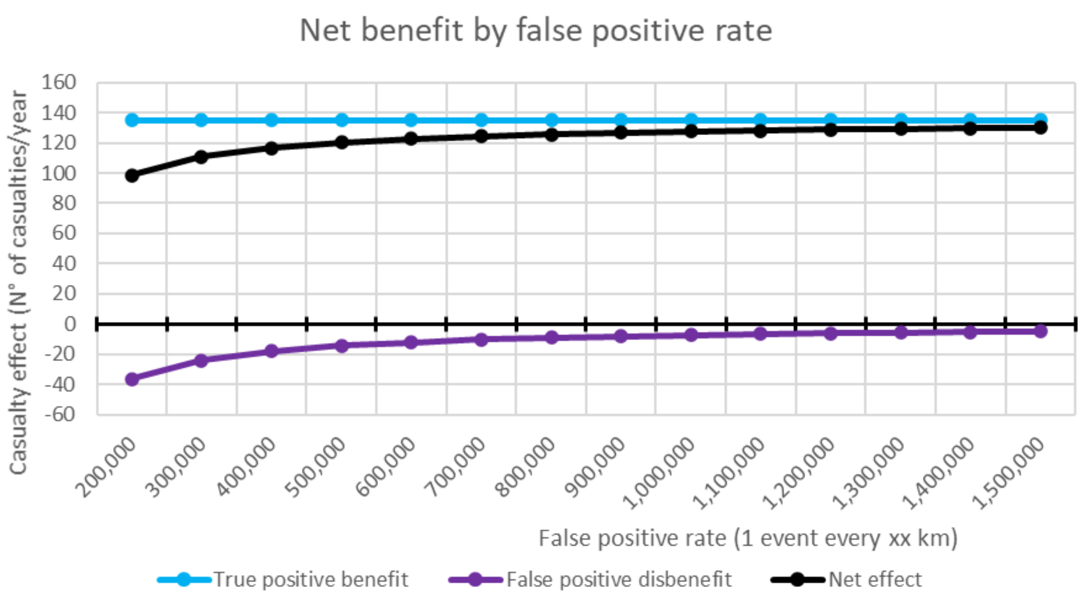


Figure 46: True positive, false positive and net casualty effect (all casualty types) by false positive rate – AEB_{max}

A similar pattern is observed for the other AEB variants considered in the analysis (AEB_{cap5} and AEB_{cap7}) where a small disbenefit for bus occupants is seen in comparison to a much larger true positive benefit.

The AEB variants offering a greater braking performance offer a greater potential to prevent casualties but come with a greater risk of injuring bus occupants as a result.

For the CCTV analysis of braking incidents (Section 3), bus occupant casualties were categorised by gender and three broad age groups: child, adult, elderly. This breakdown (Figure 47) shows that most casualties (58%) were adults, with the remainder split quite evenly between children and the elderly. For the adult and elderly age groups, females made up 74% of casualties. This is consistent with other studies of bus occupant falls e.g. (Krasna *et al.*, 2021). It is also consistent with the distribution of all London bus occupant casualties reported in STATS19 for 2017-19.

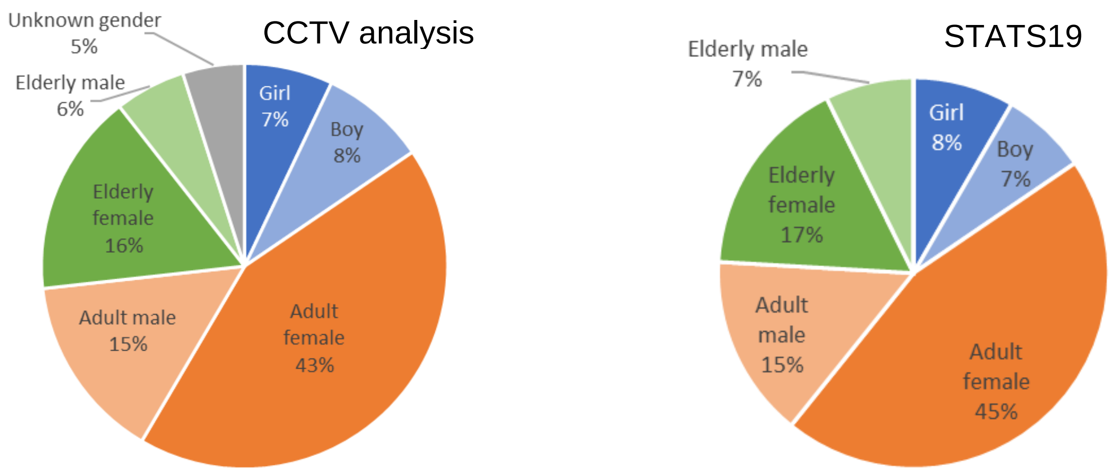


Figure 47: Breakdown of bus occupant casualties by age group (left: CCTV analysis, right: STATS19 – In London 2017-19)

In contrast TfL's Travel in London report (Transport for London, 2020) showed that cyclists in London are most likely to be white males, with women, people of non-white backgrounds and older people, underrepresented among those who cycle in comparison to their relative presence in the general population. STATS19 data (Figure 48) also shows that nearly two-thirds of cyclist casualties in London from collisions with a bus were adult males, which suggests that collision involvement is broadly in line with exposure to risk.

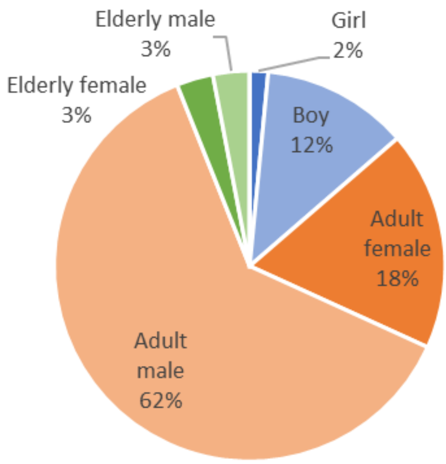


Figure 48: Breakdown of cyclist casualties from collisions involving a bus in London by age group (Source: STATS19 2017-19)

Analysis of the STATS19 database showed that adult males accounted for around half of all pedestrian and car occupant casualties, with adult females representing about one-third of casualties (Figure 49).

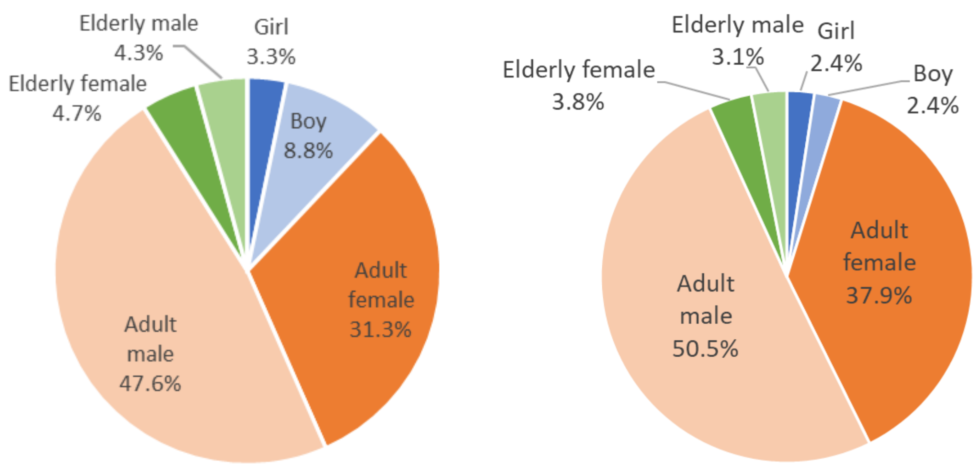


Figure 49: Breakdown of pedestrian (left) and car occupant (right) casualties from collisions involving a bus in London by age group (Source: STATS19 2017-19)

The wider results reported earlier have shown that the primary benefit of AEB on city buses is to those outside of the vehicle, with pedestrians being the dominant beneficiary. Pedestrian collisions are relatively frequently fatal. Those that may be at increased risk are bus occupants: they benefit from collision avoidance but the disbenefits under braking are likely to outweigh those benefits. However, braking incidents on buses involve fatalities only very rarely.

If it was assumed that the STATS19 age group distributions, shown in the pie charts above, was applied to the net casualty effect for each of the casualty groups, then Figure 50 shows that each age group would have a net benefit. The false positive disbenefit to the different bus occupant age groups was outweighed by the benefit to those same groups from preventing pedestrian casualties. Overall adult males and adult females might be expected to have the greatest net benefit for all casualty severities. The benefit from preventing fatalities is estimated to be more evenly distributed across adult and elderly people.

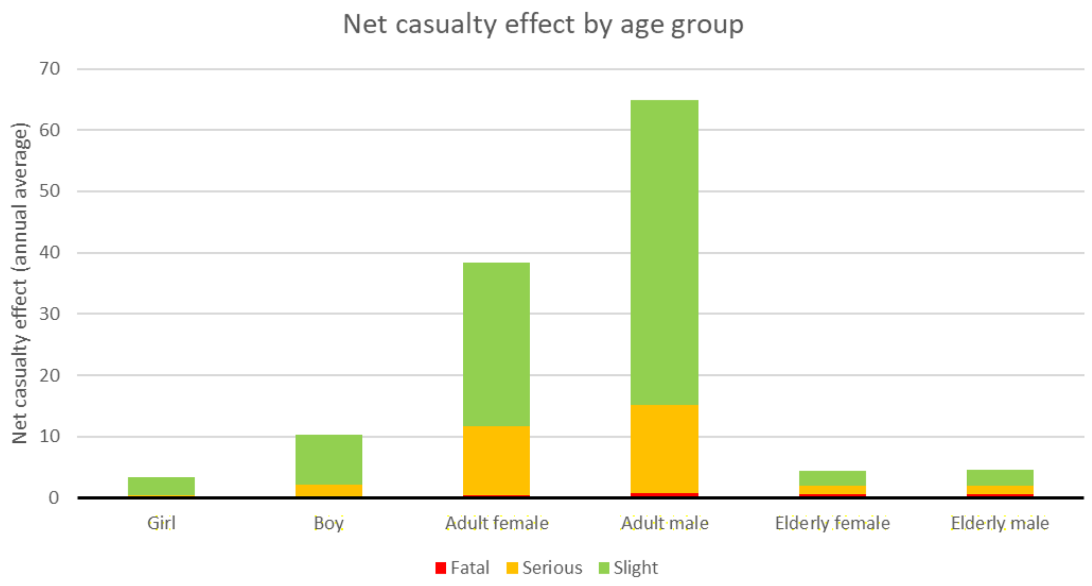


Figure 50: Average annual net casualty effect by age group – AEB$_{max}$ variant based on updated telematics and CCTV data

A sensitivity analysis of the false positive rate on the net casualty effect by age group showed that some net disbenefit was found for elderly females once the false positive rate reached a level of 1 event every 200,000km. If the net monetised casualty effect was considered then a net monetised disbenefit was found for girls once the false positive rate reached a level of 1 event every 80,000-100,000km. If it is important to avoid the risk of disbenefit to any demographic group then this might suggest that the minimum distance between false positive events should be 300,000km or greater.

The above analysis does not include full disaggregation of all protected characteristics and only includes an indication of age and gender that was able to be identified through this analysis.

7.2 Alternative braking characteristics

The analyses presented by (Knight *et al.*, 2019) were all in relation to the value of peak deceleration observed. This was primarily because it was the only measure reliably available from the original CCTV analysis. However, the theory and experimentation evidence suggest that factors such as rate of change of deceleration (jerk) and duration of deceleration (or change in velocity) could also influence casualty risk.

The CCTV analysis within this study was designed and undertaken to allow at least some of these other variables to be analysed. This section summarises a breakdown of the proportion of bus occupants injured by each variable.

Unfortunately, although the rate of change of deceleration (jerk) could be measured within the naturalistic driving data (telematics) it was not possible to measure it from the CCTV footage because the sample rate was too low, and it would require extensive manual frame by frame analysis to extract an acceleration time history: a high effort burden for a poor-quality output. It was possible to measure the time taken for the bus to reach its peak deceleration. This variable can be considered as an average rate of jerk over the period of the brake application before peak deceleration is reached. This was used as a proxy for jerk but is subject to some limitations. While it will be a good proxy for jerk in a rapid emergency brake application, it can be very poor in other circumstances. For example, where a driver applies gentle check braking for a significant period of time, say 5 or 6 seconds, and then sees a need to brake harshly, the time to peak will be long, approximating to a low average jerk. However, in reality, the actual jerk experienced in the emergency phase only will be quite high such that time to peak is a poor proxy for jerk.

The earlier analysis by peak deceleration showed a clear trend for an increasing number of casualties per deceleration event as the value of peak deceleration increased (Figure 51).

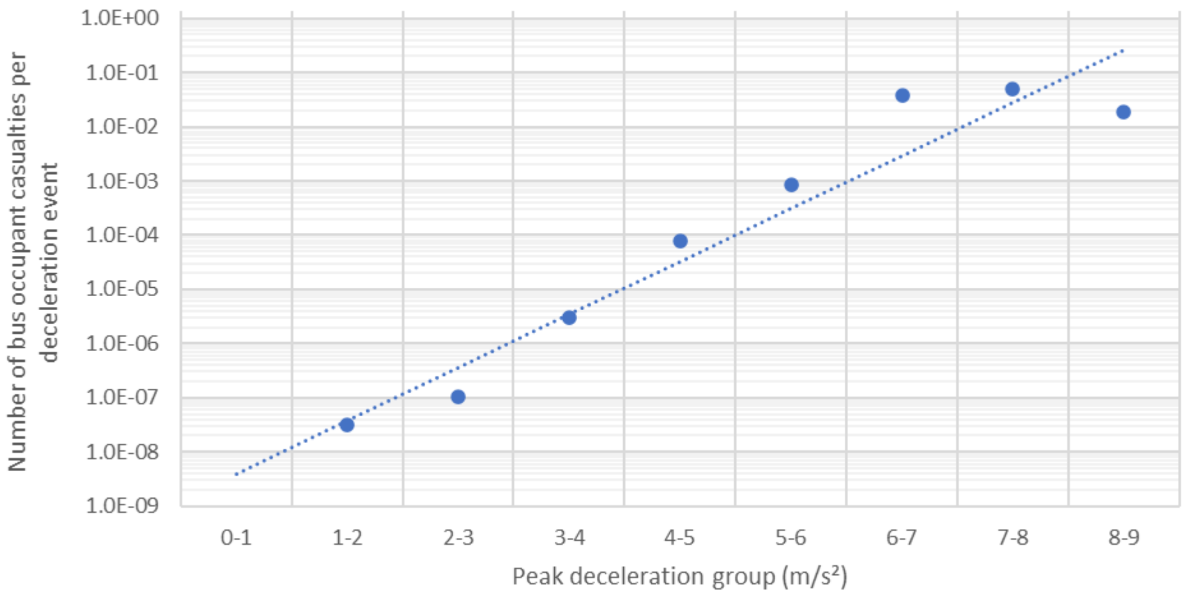


Figure 51: Relationship between casualties per event and peak deceleration

A similar analysis was carried out for a range of other variables specifically time to reach peak deceleration (in seconds and as a % of event duration), bus speed at the start of the deceleration event, duration of deceleration event and change in speed during deceleration event.

For each variable, the distribution of events per km from the telematics data was combined with the distribution of the bus occupant casualties from the CCTV analysis to estimate a relationship for the number of casualties per braking event.

Initially when considering the time taken to reach the peak value of deceleration (effectively average jerk), the absolute value (in seconds) was considered. This showed that most casualties (76%) occurred when the peak was reached within 1.5 seconds of the brakes being applied. However, the naturalistic driving data also showed that these events were more frequent in normal service. The net outcome is that the difference in risk appears small over the range in which AEB might operate (<1s time to peak), although there is a suggestion that brake applications where the overall time to peak is much longer may present a substantially lower risk (Figure 52).

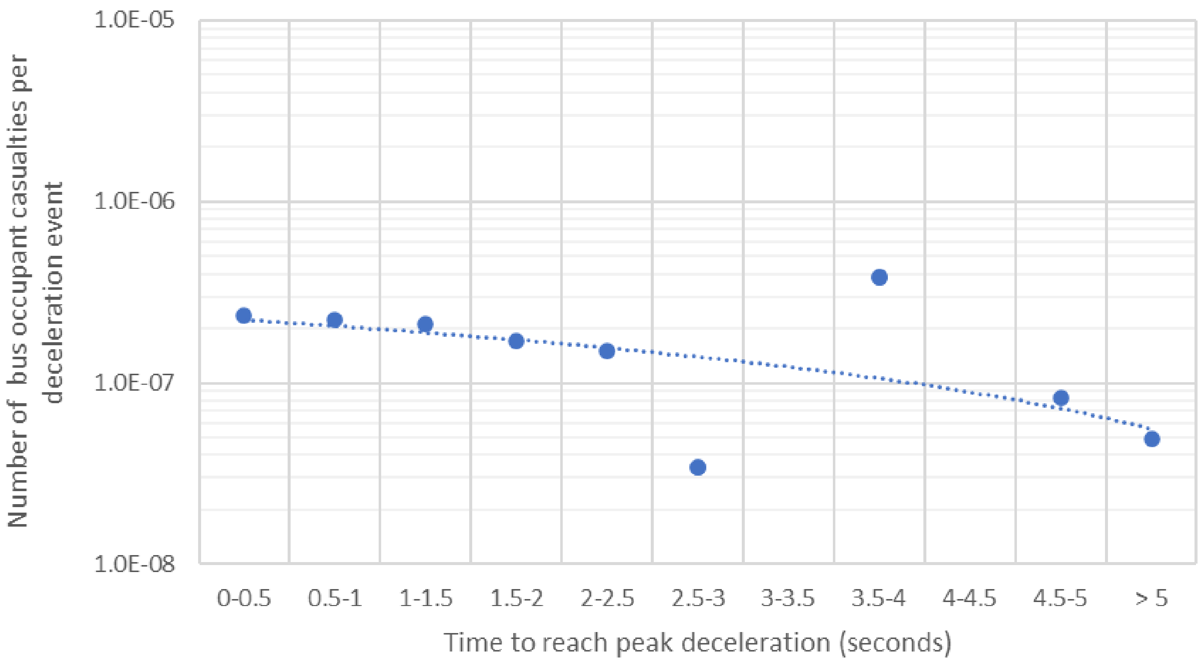


Figure 52: Relationship between casualties per event and time to reach peak deceleration (seconds)[8]

Since the length of a deceleration event can vary considerably depending on the circumstances, the time to reach the peak value of deceleration was also considered as a percentage of the overall duration of the event, e.g., did the peak occur after 10% of the duration or 90% of the duration?

Figure 53 shows the casualties per deceleration event by time to peak (% of duration). It shows that the risk of casualties is higher when the peak occurs in the first half of the brake application, with an order of magnitude decline as the peak gets closer to the end of the brake application.

[8] From the CCTV analysis there were no casualties recorded when the time to peak was 3-3.5 seconds or 4-4.5 seconds. Therefore, there are no data points for these groups in the chart.

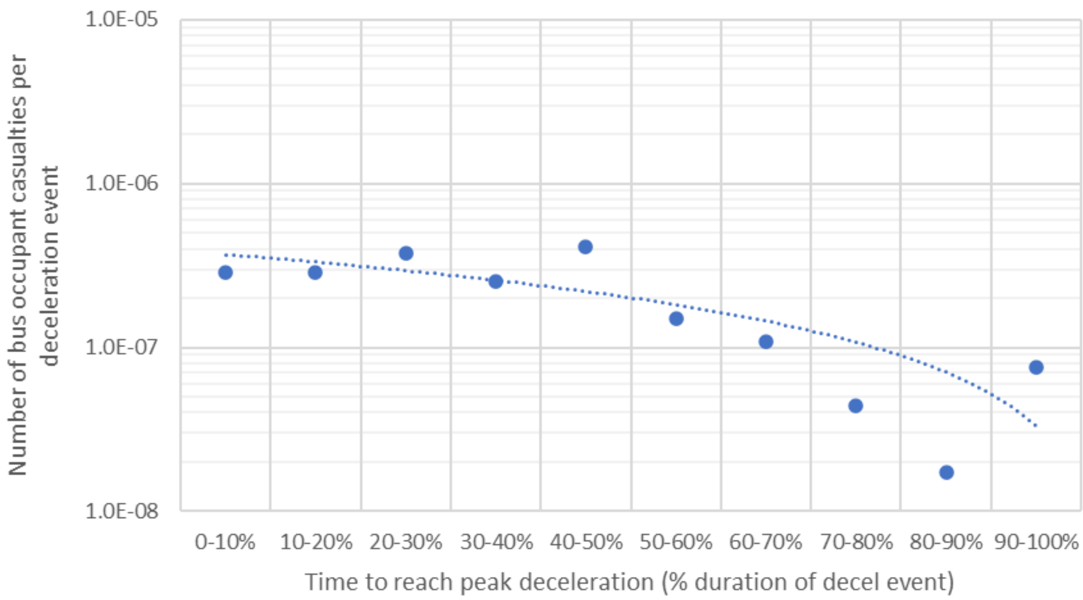


Figure 53: Relationship between casualties per event and time to reach peak deceleration (% of event duration)

This implies a possible link to brake jerk but, compared to a difference of six orders of magnitude in the risk with peak deceleration (Figure 51), any effect is considerably smaller.

Similar analyses were undertaken for mean deceleration, initial velocity, change in velocity and overall duration of brake application. The results were generally similar to those reported above with, at most, some smaller influence on the risk (number of casualties per braking event). At this stage, and subject to the limitations of the analysis in respect of jerk, it can only be concluded that any influence on passenger risk of braking characteristics other than peak acceleration is several orders of magnitude smaller and less significant. Consideration for jerk specifically is less confident than for the other parameters because it could not be directly measured in the CCTV data.

Repeating that aspect of this study with improved recording equipment capable of directly measuring jerk would substantially improve confidence in this respect. However, the larger sample of telematics data gathered in this project has shown that the number of falls per heavy brake application is far less than previously thought, this means that the benefit of doing this additional work is less than previously thought. It is much less likely to have a substantial influence on the overall conclusion than previously thought. The costs of equipping buses with specialist equipment capable of better recording of jerk, at sufficient scale to capture a substantial number of real collisions and in a time frame that can inform developments ahead of TfL's planned 2024 implementation of AEB, is potentially quite high.

7.3 Drivetrain

As described in Section 4.1.1, the mix of vehicles used to gather data on naturalistic driving behaviour comprised of a mix of diesel, hybrid and electric buses, roughly in proportion to that of London's current fleet.

A breakdown of the frequency of deceleration events per km travelled by the different drivetrains (Figure 54) shows some differences between them.

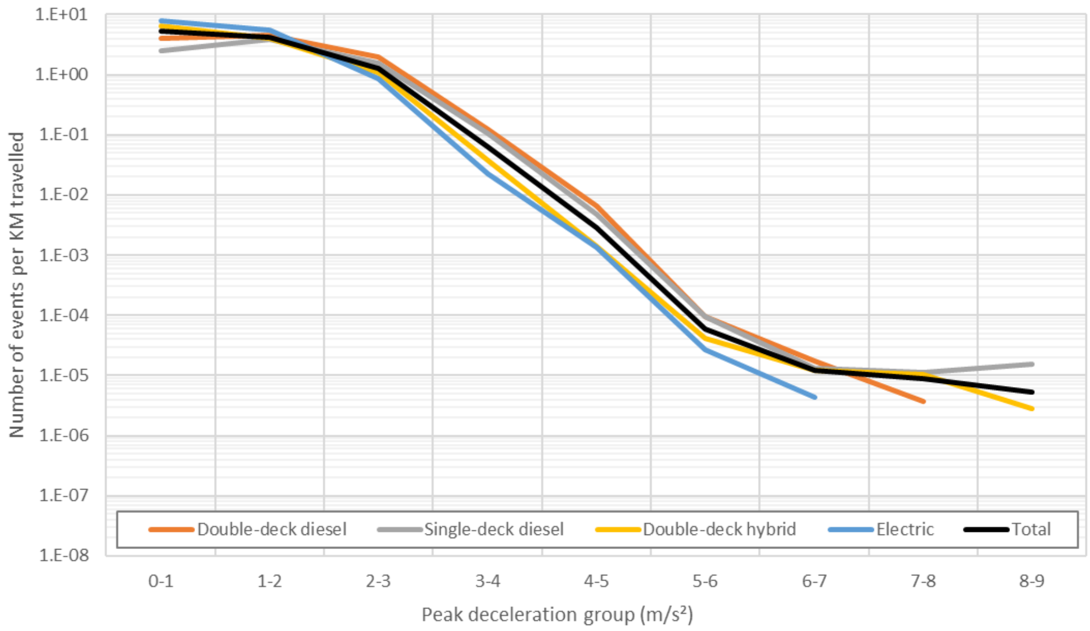


Figure 54: Deceleration events per km travelled by peak deceleration and drivetrain, including an adjustment for empty buses

Until the very highest levels of deceleration, the diesel-powered buses had a slightly greater frequency of events than the hybrid or electric buses. In fact, the electric buses did not record any braking events greater than 7m/s² during the six months in which they were monitored. The electric buses covered the least distance of the types, slightly less than the double-decker diesels which themselves only recorded eight braking events above 7m/s² during the six months. Therefore, it may simply be that they would have experienced a heavier braking event if they had been monitored over a longer period.

Each major interval of the vertical scale in Figure 54 represents a difference of an order of magnitude. Therefore, although the lines appear relatively close together, there is close to an order of magnitude difference between the frequency of braking events for the diesel and electric vehicles in some places.

To calculate the net casualty effect, the frequency of events for each drivetrain was considered in isolation to simulate the whole London fleet being of this type. For the electric and double-deck diesel buses, the data was extrapolated in line with the overall trend (black line) to provide estimated data points for the highest rates of deceleration missing for these types, as shown by the dashed lines in Figure 55.

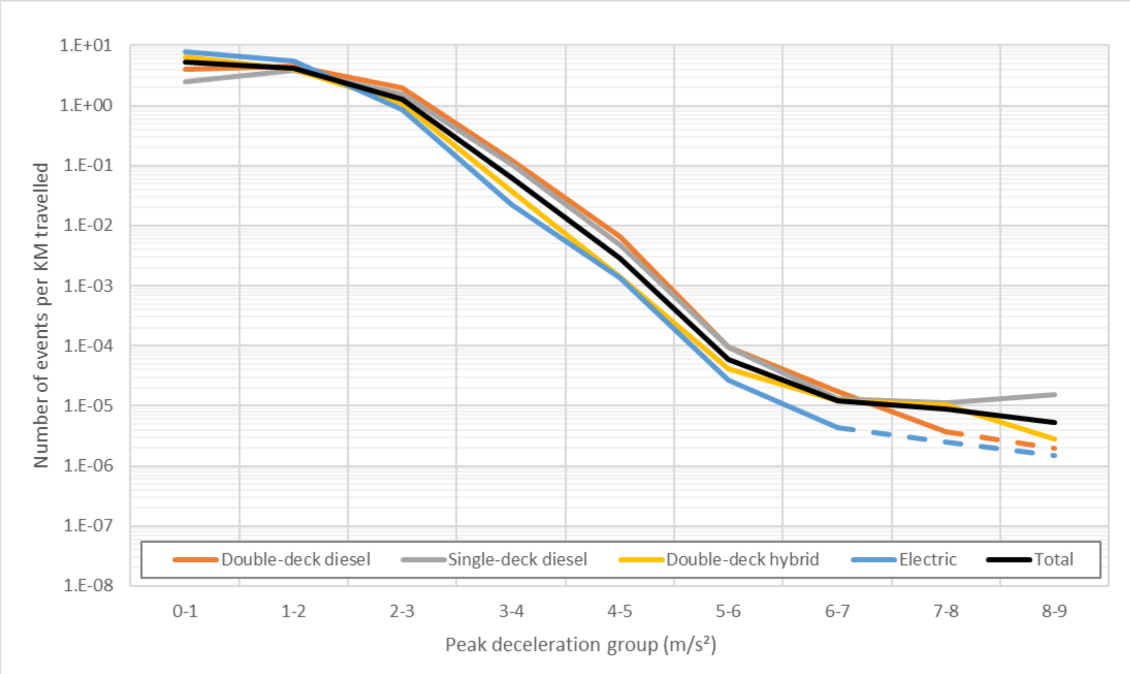


Figure 55: Deceleration events per km travelled by peak deceleration and drivetrain with extrapolation for missing data points, including an adjustment for empty buses

The results of the casualty analysis are presented in Figure 56 which shows that the lower frequency of heavy braking events for double-deck diesels and electric vehicles would make them more sensitive to the false positive rate, although all drivetrains still offer a net casualty saving across all false positive rates assessed.

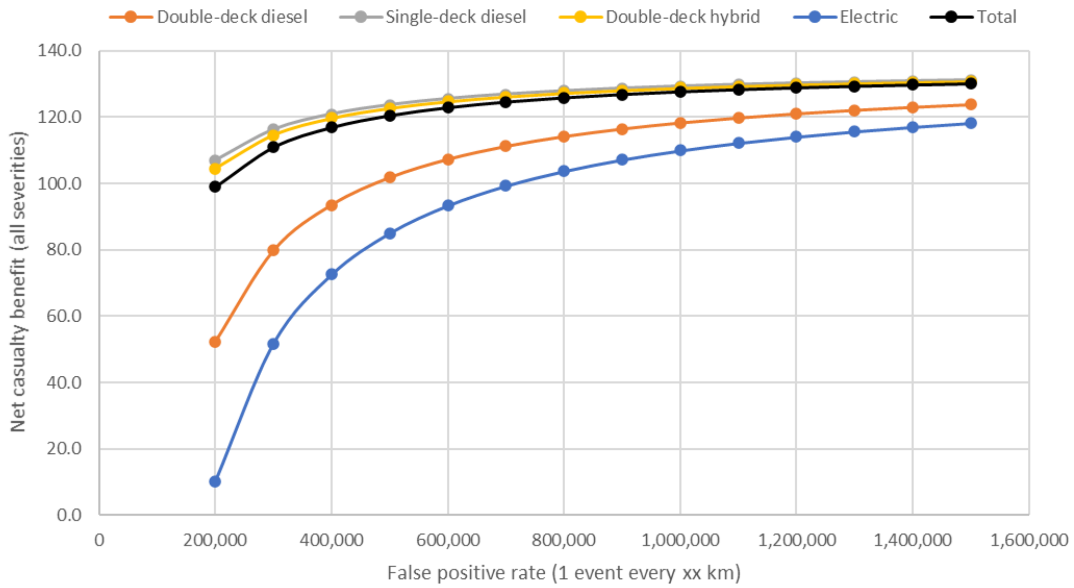


Figure 56: Net casualty effect (all casualty types) by false positive rate for different drivetrains – AEB_{max}

When considered as a monetised benefit (Figure 57) the sensitivity is less pronounced.

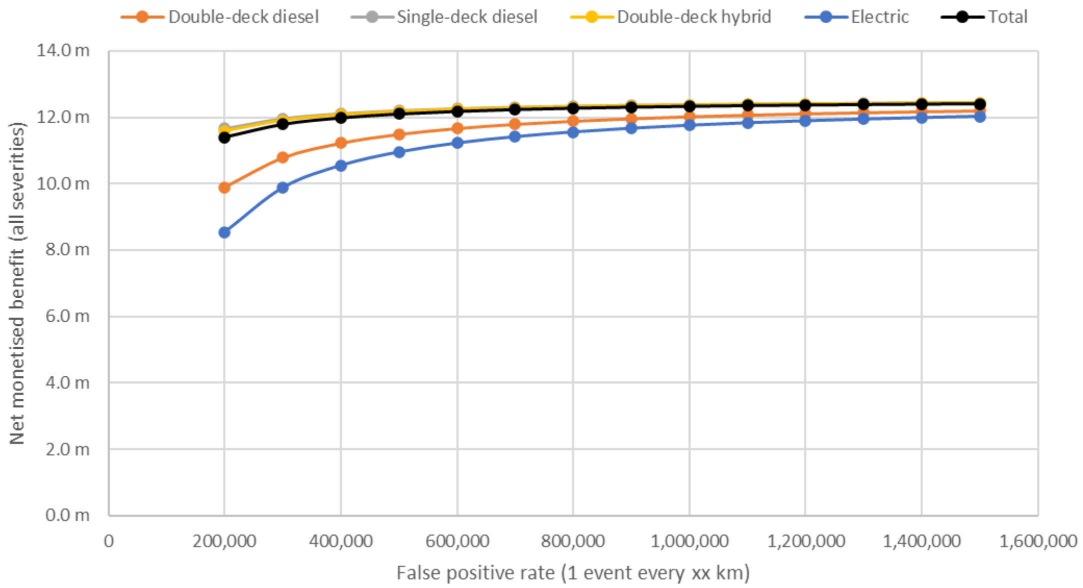


Figure 57: Net monetised casualty effect (all casualty types) by false positive rate for different drivetrains – AEB_{max}

The reduced sensitivity arises because much of the disbenefit that causes the reduction in the casualty benefit is from slight casualties which have a much lower monetised value in comparison to the value of the true positive fatalities that could be saved by the fitment of AEB.

Substantial uncertainty remains in this result. By extrapolating the data for the electric and double-deck diesel to include the highest levels of deceleration it is being assumed that if these vehicles covered enough distance then they would eventually have a braking event of this magnitude and that the rate at which bus occupants are injured remains constant. But if the data recorded (without the extrapolated points) is representative and these highest decelerations are not reached by the electric or double decked diesel buses then the casualty analysis changes dramatically. The highest peak deceleration events that have the greatest risk of injury to bus occupants are eliminated and so the electric drivetrain now offers the most potential casualty benefit from the fitment of AEB.

In addition to this, the separate Greenroad data with a larger sample size but some restrictions and ambiguities about the highest levels of deceleration, appears to show a quite different pattern. Up to a deceleration of 6.5m/s^2 electric vehicles are showing the highest frequency of brake applications, in complete contrast to the main analysis. Despite ambiguities, the data available suggests this remains true even at deceleration levels above 6.5 m/s^2, though this is not shown due to the uncertainty.

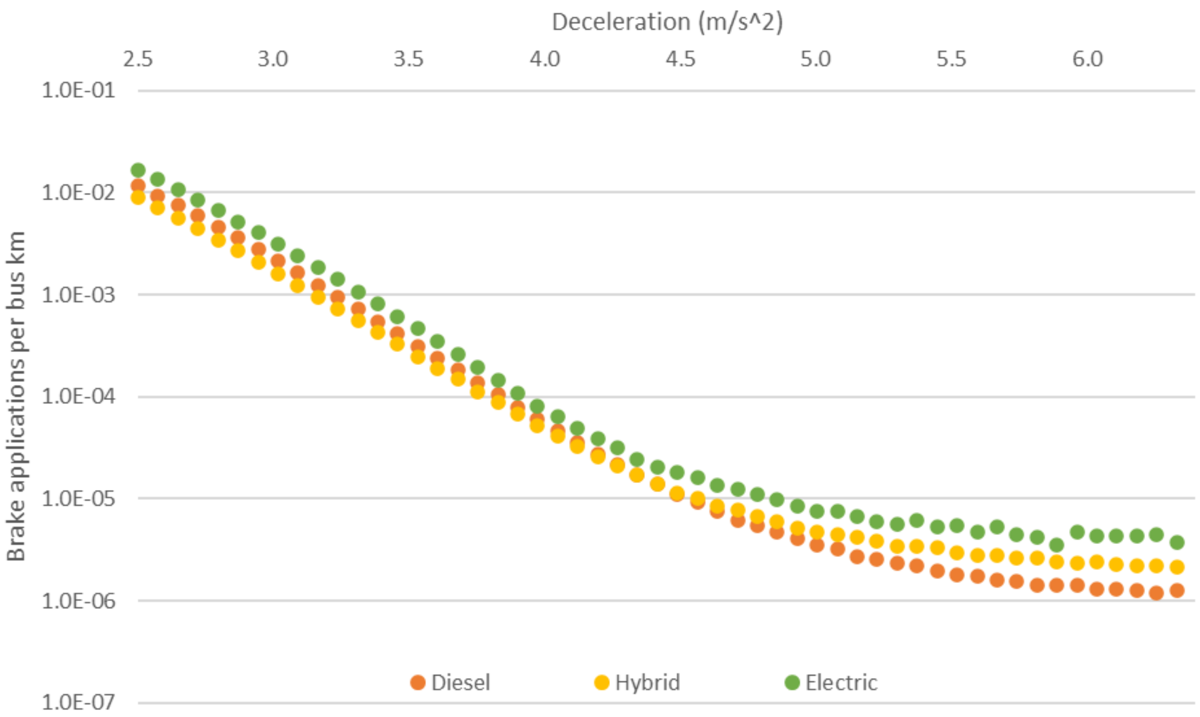


Figure 58: Frequency of brake applications by deceleration level and powertrain in the full 2009-2020 Greenroad sample (close to 1 billion km – 55% diesel, 41% hybrid, 4% electric)

The presence of regenerative braking on hybrid and electric vehicles is just one factor that may lie behind the differences. Most electric vehicles already in the TfL fleet are single deck buses and as such the routes they are used on will not necessarily be representative of all London routes they may be used on in future. Electric vehicles may also have higher torque and acceleration potential, which combined with use on different, less busy routes, could affect speeds and the interaction with other traffic.

Thus, it is not possible at this time to be confident of the final relationship in a future London fleet comprised mainly of EVs. The potential for a changed relationship should be remembered as a risk factor for slips trips and falls under braking generally, and the implementation of AEB specifically.

8 External influences

Significant actions outside of the project team have had substantial effects on developments since the work of (Knight *et al.*, 2019). The bus industry as a whole has responded positively but cautiously to the challenge to produce vehicles with AEB by 2024. In general, they are keen to act but have been challenged both by concerns over the effect on passengers and the high level of financial investment required in difficult market conditions for bus manufacturers. In fact, the prototype tested by (Knight *et al.*, 2019) has not yet been developed to production because of the investment required.

This project to increase the robustness of findings related to the relative benefits and risks to VRUs and bus occupants was partly undertaken to help provide a more comprehensive basis on which manufacturers could analyse their internal safety cases.

Earlier this year, the UNECE agreed to create a working group to examine enhancements to Regulation 131 governing the performance of AEB systems for heavy duty vehicles (buses designed for standing passengers are currently exempt and performance is only required in response to front to rear collisions with other vehicles). In addition to technical improvements in the existing regulation, the group is working on technical requirements to govern systems sensitive to pedestrians. At the time of writing, this is not expected to cover buses designed for standees (city buses). However, developing systems for the much larger volume truck market, whose braking systems and general operating environments share much more in common with buses than passenger cars, could possibly help with the scale of investment needed, if for example, development costs can be shared across sales of both trucks and buses.

Perhaps most significantly, Mercedes has begun to market a bus with an AEB system capable of responding to vehicle front to rear collisions and those with moving pedestrians. Marketing material for this system[9] states that the system will apply **partial** braking when imminent risk of collision is detected. This strategy for implementing AEB is different to that of the prototype tested by (Knight *et al.*, 2019), which applied whatever level of braking was calculated as necessary up to the maximum the bus brakes could deliver.

Where the level of braking the AEB system commands is less than the maximum the bus's brakes can produce (e.g. the system is capped at $5m/s^2$ when the brakes can produce $9m/s^2$), then there is an incentive to intervene earlier wherever possible to maintain a high effectiveness. In general, systems will become more confident in their prediction of an imminent collision the closer to that collision that they get. Thus, intervening earlier can mean intervening at a time when the system is less confident of the collision risk. This can lead to increased false positives. However, the analysis in this project has shown that it is the higher rates of deceleration that give the greatest risk of injury to bus occupants during false positives. Therefore, where the magnitude of maximum AEB commanded braking is less, the consequences of false positives are less, so this might be considered more tolerable.

[9] See for example https://www.mercedes-benz-bus.com/en_GB/models/citaro-hybrid/safety/safe-driving.html

As such, it is quite possible that several other aspects of the Mercedes strategy for bus AEB differ to that of the prototype tested by (Knight *et al.*, 2019). These differences could also influence the detailed definition of the TfL AEB standard. There will naturally be a variety of approaches taken by different bus manufacturers in their application of AEB. Testing of the systems, combined with monitoring in use, will give TfL the means to evaluate the most effective approaches for the London context, and to update their specification and/or test protocols over time as they learn about the implementation. This is an approach that is well demonstrated by Euro NCAP for example, and their use of a roadmap and updated protocols over time to keep raising the safety standards required of new cars.

9 Potential policy options

9.1 Summary of evidence

While there is some evidence to suggest variations between different fleets, routes or periods of time, the overwhelming weight of evidence from millions of bus km strongly suggests that emergency level braking of buses (> 6 m/s^2) is substantially more frequent than was originally estimated by (Knight *et al.*, 2019) on the basis of a 400 km road trial. Nearly quadrupling the sample size of the CCTV incident database for passenger falls under braking, broadly confirmed the original distribution of casualties by deceleration level, with only relatively minor changes.

These new findings very substantially changed the conclusions of (Knight *et al.*, 2019) in relation to the influence of false positive rate and maximum AEB deceleration. (Knight *et al.*, 2019) concluded that AEB applying the maximum braking possible was the best system for fatality reduction, if it produced false positives less frequently than once every 600,000km. However, it could result in an adverse effect on the total number of casualties if false positives occurred more frequently than once every 700,000 km. At this level there would still be a benefit for the serious and fatal casualties such that the net monetised benefit remained strong. It was found that capping the maximum deceleration a system could apply would reduce the benefit in true positive situation, but the reduced impact of false positives meant that systems would have a better net benefit when the distance between false positives was lower.

The results of the current study change these conclusions and strongly suggest that applying maximum braking offers the best outcome in terms of net monetised benefit for all false positive rates assessed (once every 200,000km or more). If only the count of total casualties is considered, then there remains a strong net benefit of maximum braking across the false positive rates considered. If more frequent false positive rates are considered (i.e., less than 200,00km between incidents) then the benefit is seen to decline considerably (Figure 59). The AEB variant applying the maximum braking possible (AEB_high) was still the best system for fatality reduction, if it produced false positives less frequently than once every 40,000km.

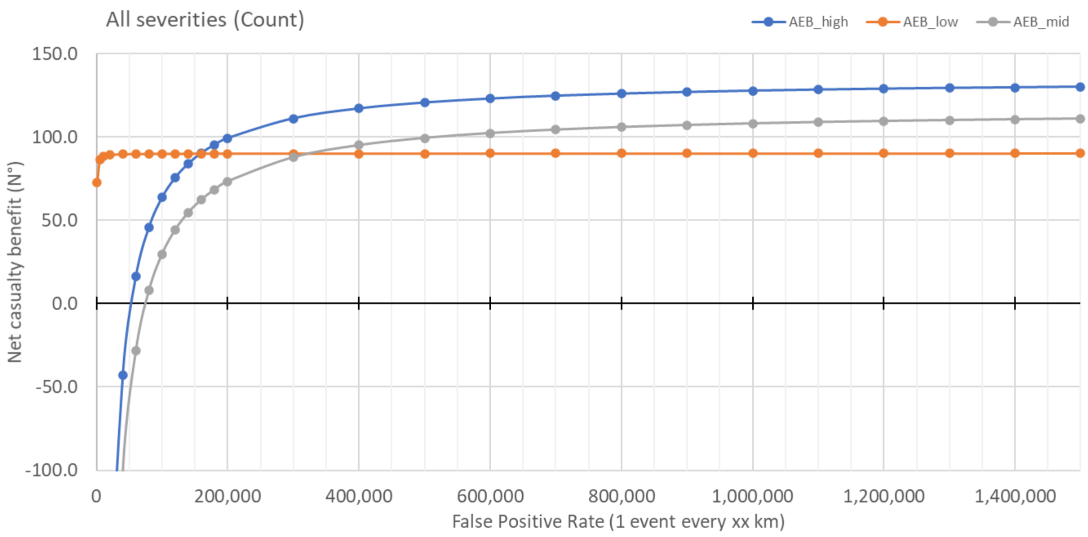


Figure 59: The effect of false positive rate on the annual net casualty benefit of each candidate AEB system (central prediction) with an extended range of false positive rates.
(Using updated data from CCTV and telematics analysis and adjusted for empty buses)

Further analysis suggests that, in most scenarios of how transport in London might change post pandemic, the total net benefit of AEB increases. In the two where it decreases, it does so only by a small margin, and this does not reverse the overall benefit.

Analysis of how AEB affects different road user groups is interesting. Although even for maximum braking systems, there remains a strong net benefit to those casualties that are only slightly injured, this does not mean there is always a benefit to bus occupants. Bus occupants will in a proportion of cases benefit from AEB avoiding or mitigating collisions with other vehicles. However, this benefit is neutralised by the disbenefit of AEB applying slightly harder braking on average than typical drivers manage in pedestrian collisions. Thus, even if no false positives occur, the model predicts a very small disbenefit to bus occupants. Limiting the maximum deceleration would not substantially change this because it would limit both benefit and disbenefit.

The small disbenefit is not particularly sensitive to false positive rate where systems achieve more than around 600,000 km between events. At rates worse than this the disbenefit grows slightly more quickly. A similar pattern is seen for the variant limited to 7m/s^2 and limiting maximum deceleration to 5 m/s^2 would eliminate this dependency on false positive rate.

All of the above is based on evidence and relationships built around peak deceleration as the sole way to characterise braking severity. Investigation of other parameters such as brake jerk, duration, initial speed, change in speed etc have shown no or minimal influence on braking severity with only the time to reach peak deceleration showing a small effect. However, this analysis cannot be considered definitive because the CCTV systems used on buses do not record acceleration data at high frequency, so proper measures of brake jerk could not be calculated leaving simplistic measures like time to peak as the only possible proxies. It is, therefore, possible that future analyses may be better able to identify other relationships and it is not possible to completely rule out the influence of these other parameters.

9.2 Potential policy options

So, what does this all mean for TfL's policy with respect to the fitment and evaluation of AEB on London buses? The current wording of TfL's Specification for New Buses in respect of AEB is that:

- systems must be tested according to the protocol developed by (Knight *et al.*, 2019) and achieve a score in excess of zero
- AEB activation must be recorded in CCTV systems to allow investigation of true or false positive incidents
- the manufacturer must provide evidence that the false positive rate in service will be better than one every [600,000km][10]

The method by which a manufacturer shall demonstrate compliance with the false positive rate requirement is not specified in the document itself. It was anticipated that this would take a documented safety case approach analogous to that used by manufacturers to demonstrate compliance with similar open requirements for complex electronic control systems within many international regulations (e.g. UNECE Regulation 13 on braking, etc).

Achieving a score in excess of zero in the test effectively means passing a few simple pre-requisite requirements – it must achieve some speed reduction in the least demanding true positive test, default to being switched on, and pass the 'bus stop' false positive test. This low standard of performance was set because of the uncertainty around the relationship between true positive benefits and false positive risks and whether capping the maximum deceleration was likely to be beneficial or not. Essentially, these decisions were left to the market to develop systems they thought to be safest.

Given the results of the current study, several options could be considered. The options are set out below, with any associated amendments to the specification text suggested and highlighted in yellow.

1. **Do Nothing**. This means the current policy would be retained. This would fail to guarantee that all systems offered strong potential benefits in true positive situations, relying on industry to voluntarily exceed the minimum performance required to pass the test protocol. Considering the results from the current study, this option would guarantee that the net effect on casualties as a whole group would be positive regardless of whether counting casualties or valuing

[10] Square brackets indicate a provisional value that may be updated based upon improved fleet data as the system is implemented in London.

financially or whether considering all severities or just more severe collisions. It would also ensure that the predicted net adverse effect on bus occupants was minimised even for systems applying maximum braking. However, any bus using an AEB strategy that permits more frequent false positives but minimises the risks by capping maximum deceleration and attempting to compensate effectiveness through early intervention would be unlikely to meet the criteria. It would continue to set a very high bar in terms of false positive performance to new entrants in the market, which may influence investment decisions.

2. **Decrease minimum average distance between false positive events.** Applying the same criteria for selecting a false positive limit as originally used (max braking variant most effective for fatalities, small net disbenefit for slight casualties tolerated and overall a strong net monetised effect) would suggest that the false positive limit could be reduced to at least 300,000 (lowest assessed in the research) without causing a net disbenefit to any particular demographic group. Assuming systems voluntarily exceed the current true positive threshold, which is set low, the systems would still provide net benefits comparable or better to those originally envisaged. This may lower one barrier to entry for manufacturers looking to produce AEB for buses and increase the chance of TfL being able to purchase equipped buses by 2024. This is only the case though, if the manufacturer’s own internal standards for duty of care permit them to produce a system with those characteristics and without validation over much larger distances.

    New specification text to enable this change:

    The bus OEM must produce documentary evidence for LBSL approval to demonstrate that on average they would expect false positive activations in mixed London traffic less frequently than once every [~~6~~300,000]km per vehicle.

3. **Set a variable minimum distance between false positives dependent on maximum deceleration.** This option would allow the real-life trade-offs between true and false positive performance to be better reflected in the standard. The logic would be that a high false positive rate can be tolerated if the effect on bus occupants (max braking) is low. A high effect on bus occupants of false positives (high max braking) can be tolerated if the frequency with which they occur is very low. This could be implemented in a number of ways, with for example a sliding scale defined by a mathematical formula, a set of categories based on peak deceleration with different limit values, or a simple definition of a false positive event as one where the peak deceleration exceeds 5 m/s^2. This option would ensure the risk to bus occupants remained as low as possible given different approaches to the true positive benefit. It will allow early adopters of the technology access to a market for products that might take a cautious or a staged approach. However, in isolation, this option would provide no incentive to manufacturers to design systems with the highest levels of true positive performance or offer any reward for those that do so voluntarily. So there is a risk that there is no incentive to offer anything other than the least beneficial combination unless the requirements are updated in future phases of the roadmap.

New specification text:

The bus OEM must produce documentary evidence for LBSL approval to demonstrate that on average they would expect false positive activations in mixed London traffic less frequently than once every [600,000]km per vehicle, where a false positive event is defined as an AEB activation where the peak deceleration exceeds [5] m/s².

Alternatively:

The bus OEM must produce documentary evidence for LBSL approval to demonstrate that on average they would expect false positive activations in mixed London traffic less frequently than shown in table xx

Max AEB Deceleration (m/s²	*<5*	*5-6*	*6-7*	*7-8*	*≥8*
Min distance between false positive events (km)	*300,000*	*400,000*	*500,000*	*600,000*	*700,000*

4. **Clarify that false positive evaluation undertaken in other markets should qualify**. Some system manufacturers may first develop bus AEB for a market outside London. Accumulating the road test mileage to prove the false positive threshold is met is a substantial undertaking and manufacturers may be unwilling to repeat the exercise in full in each city market they sell into. There is an option therefore to allow testing undertaken outside of London to count within the evidence requirements, which is not explicit in the current specification and could be clarified. Any evidence should be relevant to London's roads and consequently permitted evidence should avoid, for example:

    - motorway mileage
    - mileage in a relatively new city using a grid system with straight wide streets, regular pedestrian underpasses, and no street parking.

    New specification text to enable this change:

    The bus OEM must produce documentary evidence for LBSL approval to demonstrate that on average they would expect false positive less frequently than once every [600,000]km per vehicle. The evidence should be based on experience of the system in London or another city with a transport network of comparable density and complexity with a similar cross section of junction types, vehicles and road users.

5. **Increase minimum true positive performance.** The results of this study and the fact that the market has produced at least one production bus model with AEB clearly show that the level of caution initially applied in setting the low standard is no longer in keeping with the evidence. The factor limiting how high the bar is set for true positive performance is no longer concern about the risk to bus passengers outweighing the wider benefit but what industry are technically able and commercially willing to deliver. Any values up to a level just

below what the prototype system tested by (Knight *et al.*, 2019) could be set but TfL may wish to consider a lower standard, or staging performance initially lower and higher later, if consultation with industry suggests this could make it easier to deliver beneficial solutions to the market in the short term and more beneficial ones in the longer term as experience with the systems grows. The performance value would have to be defined based on more testing of bus AEB systems (potentially both market-ready and prototype), and in consultation with industry.

New specification text:

It shall be tested in accordance with LBSL's Test & Assessment protocol for AEB (Attachment 15) and it must attain a performance score greater than ~~zero~~ [X]. Value to be defined in consultation with industry.

6. **Update the requirements over time via the BSS Roadmap.** The BSS roadmap sets out the requirements for the future TfL fleet of new buses. It would be feasible to use this roadmap to raise the performance of AEB systems over time. For it could be achieved by:

- Option 2: A lower distance between false positive braking events could be set initially, and then the distance increased over time.

  New specification text to enable this change:

  The bus OEM must produce documentary evidence for LBSL approval to demonstrate that on average they would expect false positive activations in mixed London traffic less frequently than ~~once every [600,000]km per vehicle.~~the distance per vehicle indicated:

BSS roadmap year	*2024*	*2027*
Distance per vehicle between false positive activations in mixed London traffic	*[300,000]km*	*[600,000]km*

- Option 3: Setting a variable minimum distance between false positives dependent on maximum deceleration, and then changing or removing the scale over time.
- Option 5: Increase minimum true positive performance by using thresholds that increase over time.

  New specification text:

  It shall be tested in accordance with LBSL's Test & Assessment protocol for AEB (Attachment 15) and it must attain a performance score greater than ~~zero~~ the scores defined in the table below. Value to be defined in consultation with industry.

BSS roadmap year	*2024*	*2027*	*2030*
Performance score of new buses shall be greater than:	*[X]*	*[Y]*	*[Z]*

9.3 Discussion

It is useful to consider how a combination of policy options might affect the casualty saving outcome and the ability of the market to deliver systems. As a reminder the policy options are:

1. Do nothing
2. Decrease minimum distance between false positive events
3. Set a variable minimum distance between false positives dependent on maximum deceleration
4. Allow false positive evaluation undertaken in other markets to qualify
5. Increase minimum true positive performance
6. Update the requirements over time via the BSS Roadmap

Option 4 which accepts evidence from other markets stands alone and could be implemented with any other option. It represents a very small increase in risk but may be quite beneficial in improving the ability of the market to provide a solution.

If option 1, or particularly options 2 or 3 were implemented without option 5 there would be a strong risk that the market might deliver cheap but ineffective systems that did not help TfL to reach it’s vision zero goal for buses. Implementing option 5 in isolation would eliminate that risk.

Combining option 5 with option 2 would risk slightly greater disbenefits to bus occupants but may make it more feasible for suppliers to enter the market.

Combining option 5 with option 3 would not be feasible if true positive performance were set so high as to require maximum braking. If true positive performance were set lower, then it would maintain the safeguards for bus occupants while allowing industry more flexibility about how they met the requirements.

It should be noted that all options that increase the risk to bus occupants but the analysis of different age groups (section 7.1) showed that all age groups had a net benefit from the fitment of AEB.

It is also important to consider the use of the BSS roadmap to influence requirements. No changes to the specification that are made for 2024 need to be seen as permanent, because the specification and roadmap working together can give industry warning of future changes. For example, the 2024 requirements might be adjusted to allow more manufacturers to enter the market, and then revised in 2027 or 2030 to ensure that maximum benefit of the AEB system is realised for London. This might allow manufacturers to refine their offering over time or have warning of future phases of requirements to aim for, or even leapfrog to the more demanding / later standards sooner.

The most appropriate combination of options to select depends strongly on the likely reaction of industry, which has not been formally assessed as part of this research. A consultation is the next step required to further inform the decision-making process.

10 Conclusions

The sample size of naturalistic driving data used to support the analysis of AEB effects has grown from 400km to a primary data set of more than 1 million km and a total of more than 1 billion km. The CCTV incident data has almost quadrupled in size to 300 cases. The evidence base can now be considered very robust.

The new data shows much higher frequencies of heavy braking which translates to a much lower predicted casualty risk from false positive braking. It is now predicted that AEB will have strong net benefits across all casualty groups at false positive rates better than one in 300,000 km. The analysis suggests that the largest net benefits will be achieved by AEB systems that apply maximum braking in emergencies.

Within this strong net benefit, analysis of the groups affected has shown that the benefits will be mainly accrued to those outside of the bus. Bus passengers will see some benefits from avoidance of collisions, but these will be slightly outweighed by risks from heavier braking than drivers typically apply in true positive emergency situations (though not heavier than good drivers can achieve) and the risk of false positives, such that on average a net disbenefit would be expected for bus passenger casualties.

The most important group of casualties outside the bus are pedestrians. There is a substantially different demographic distribution of pedestrian and bus occupant casualties with a substantially greater proportion of females and elderly people in the population of bus occupant casualties than there is in the pedestrian casualties. However, the false positive disbenefit to the different bus occupant age groups was outweighed by the benefit to those same groups from preventing pedestrian casualties. Overall adult males and adult females are expected to have the greatest net benefit for all casualty severities with the benefit from preventing fatalities being more evenly distributed across adult and elderly people.

The risk of ethical concerns from implementing AEB has been acknowledged by TfL in the commissioning of this report, and the examination of the user group and age/gender demographic effects has indicated that false positive rates better than one in 300,000 km is unlikely to cause a disbenefit to any particular demographic group. It will be important for TfL to monitor these effects over time.

Increased confidence in the robustness of the model predicting the effect, and the changes in the identification, magnitude and distribution of risks gave rise to the following potential policy options:

1. Do Nothing – low true positive performance, high false positive performance.
2. Decrease minimum average distance between false positives. Take the opportunity to reduce the stringency of false positive performance given the analysis now shows a considerably reduced risk of adverse consequences.
3. Set false positive rate in proportion to maximum deceleration. Allow an approach that flexes the standard required for false positives in relation to the likely consequences of false positives in terms of high deceleration braking.
4. Permit experience gained in other markets to be used as evidence of expected false positive rate in London. Reduce the burden on industry to prove they meet

the requirement in London by allowing evidence of good performance in comparable cities to be used in approvals.

5. Increase true positive performance. The evidence now shows high deceleration strategies produce the strongest net benefit; this option will maximise the benefit.
6. Update the requirements over time via the BSS Roadmap. The requirements can be updated in phases set out in the roadmap, in order to deliver an increase in safety performance balanced with encouraging market entry for AEB on buses as a new technology.

Implementing option 5 alone (i.e. with Option 1) would represent the safest approach (high true and false positive performance) but would be most demanding for industry to meet. Combining option 5 with options 2 or 3 and/or option 4 would still maintain a high true positive performance but may slightly increase risks for bus occupants and may make it easier for some manufacturers to develop a product. Implementing option 2 or 3 in isolation would risk the market delivering cheap but ineffective systems.

In order to best inform the choice of option, it is recommended that TfL consult with industry to identify the likely responses to each different approach.

The main aim of this project was to correct the statistical weaknesses in the original predictive model, and to assess whether this affected the case for or against AEB on buses. As such, in the core analyses, other variables have not been updated so as to avoid confusion with changes that have occurred due to other factors such as changes in the traffic levels, incident numbers etc are not taken into account. These changes have been accounted for separately in general consideration of post pandemic scenarios of future travel in London. These suggest that most scenarios tend to improve the case for AEB and none would reduce the net benefit to the levels previously predicted.

It is also important to note that this project considers bus braking data analysis and how that informs the implementation of AEB in isolation. It does not consider any other vehicle safety measures applied as part of the fuller Bus Safety Standard, nor any other pillars of TfL’s safe systems approach. The results have not been passed through to a full update to the cost benefit analysis. The Clustered Cost Benefit Analysis (CCBA) from the Phase 1 research accounts for the full package of safety measures implemented in the BSS, as well as modelling the realistic phased introduction of AEB over time. It, therefore, represents the fuller picture of AEB as part of that wider bus vehicle program.

This project has expanded the sample size for the evidence used in the initial BSS Phase 1 research on AEB. This allows a direct comparison with the previous values. There is potential for a future update of the values in the modelling, to reflect any changes in the fleet, casualties, and traffic mix over time since that initial work, however these changes are out of scope for this project to enable a clear comparison. It is possible that other strategies implemented in other safe system pillars (safe streets, speeds, users etc) will have had some effect to reduce casualties for example. In reality, unless London has undergone some dramatic changes, the results are not likely to differ substantially simply by the passage of time.

11 Acknowledgements

We would like to acknowledge the collaboration of the bus operating companies that have shared CCTV data for analysis, and particularly the operator allowing us to fit telematics units to their buses. We are also grateful for the technical input of both 21st Century and Greenroad telematics companies.

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Appendix A CCTV Database details

TfL Bus Braking - CCTV Data Capture Form

Submit Data | Reset Data

Incident Data

Field Name	Data
IncidentRowID	1
Coded By	
Bus Operator	
Incident Reference (CCTV Clip Name)	
Incident Date (DD/MM/YYYY)	
Incident Time (HH:MM:SS)	
Incident Latitude (about 50ish)	
Incident Longitude (about 0 ish)	
Acceleration data present?	
Case suitable for braking analysis?	
Case relevant to AEB - True Positive scenario?	
Case includes interesting or good "case study" footage?	
Bus Occupant(s) or VRU affected by Slips/Trips/Falls/Impacts?	
Bus braking at time of incident?	
What was the reason for braking?	
Was incident at or within 20m of a bus stop	
Road Surface conditions	
Lighting conditions	
Number of Vehicles involved (Choose 0 - 10)	1
Number of people affected by Slips/Trips/Falls/Impacts (Choose 0 - 50)	1
Incident description	

Vehicle Data

Field Name	Vehicle Details
VehicleRowID	1
Incident Reference	0
Vehicle number	1
Bus fleet number (or VRM)	
Vehicle type	
Bus type	
Vehicle Manouevre	
First point of impact	
Impact Object	
Other vehicle reference number (999 if no impact)	
Time at start of braking event (HH:MM:SS.xxx)	
Vehicle speed at start of braking event (mph)	
Time at end of braking event (HH:MM:SS.xxx)	
Vehicle speed at end of braking event (mph)	
Time at 90% Peak Decel (HH:MM:SS.xxx)	
Vehicle speed at 90% Peak Decel (mph)	
Deceleration at 90% Peak Decel (g)	
Time at 100% Peak Decel (HH:MM:SS.xxx)	
Vehicle speed at 100% Peak Decel (mph)	
Deceleration at 100% Peak Decel (g)	
Total seated bus occupants - IN POSITION	
Total seated bus occupants - OUT OF POSITION	
Total standing bus occupants	
Total transitioning bus occupants	
Total occupants moving within the vehicle	
Seated bus occupants affected by Slips/Trips/Falls/Impacts - IN POSITION	
Seated bus occupants affected by Slips/Trips/Falls/Impacts - OUT OF POSITION	
Standing bus occupants affected by Slips/Trips/Falls/Impacts	
Transitioning bus occupants affected by Slips/Trips/Falls/Impacts	
Moving bus occupants affected by Slips/Trips/Falls/Impacts	
Seated bus occupants injured - IN POSITION	
Seated bus occupants injured - OUT OF POSITION	
Standing bus occupants injured	
Transitioning bus occupant injured	
Moving bus occupants injured	
Comment	

Casualty data

Field Name	Casualty Details
CasualtyRowID	1
Incident Reference	0
Vehicle number	
Casualty Number	1
Casualty Type	
Injury Severity	
Sex	
Age	
Impairment	
Best camera view to see casualty	
BUS OCCUPANTS/DRIVER ONLY	
Occupant Action	
Occupant level	
Direction of seat (if used, N/A if standing)	
Direction the casualty was facing during incident	
Object held by casualty during incident	
Object hit by casualty during incident	
Body part contacted during incident (first point..trumped by severe)	
VRUs ONLY	
VRU movement	
Time when VRU is first on a recognisable collision course (HH:MM:SS.xxx)	
Time at VRU impact (HH:MM:SS.xxx)	
VRU speed	
Comment	

Bus Safety Standard: Bus Braking Data Analysis

Advanced Emergency Braking (AEB) is a Driver Assist system, intended to help the driver to avoid or mitigate the severity of collisions. AEB uses forward looking sensors to detect the likelihood of a collision. If the driver has not acted to prevent a detected collision, then the brakes are automatically applied to slow, or ideally, stop the vehicle before impact. Prior research has identified that AEB is effective in preventing and mitigating vehicle and pedestrian collisions. It could be the single biggest vehicle technology contributor to achieving vision zero, with potential to prevent up to around 25% of pedestrian fatalities from collisions involving buses. Currently Transport for London's Bus Safety Standard (BSS) requires the fitment of AEB to new buses from 2024 and has encouraged it since 2020.

Buses carry unrestrained and standing passengers, a minority of whom do already sustain (mainly minor) injuries due to manually applied braking. There are concerns that AEB could exacerbate the problem. A predictive model was developed to quantify the net effects in prior research. This current study was commissioned to increase the robustness of the conclusions to allow better informed decisions on the implementation of AEB and the specifications required. The sample size of naturalistic driving data was increased from 400 km to >1 million km in the core data set and >1 billion km including a supporting data set. CCTV incident data has almost quadrupled in size to 300 cases. The evidence base can now be considered very robust.

The new data predicts stronger net benefits with much less sensitivity to false positive rate than the prior study. It suggests that AEB systems applying maximum braking will provide the best outcomes. However, it was confirmed that within this large net benefit across all casualty groups, the benefits for bus occupants specifically would be slightly outweighed by disbenefits.

Increased confidence in the robustness of the model predicting the effect, and the changes in the identification, magnitude and distribution of risks gave rise to five potential policy options. In order to best inform the choice of policy option, it is recommended that TfL consult with industry to identify the likely responses to each different approach.

Other titles from this subject area

PPR932	The Transport for London Bus Safety Standard: Advanced Emergency Braking (AEB) - Evaluation of Safety Measure (2020). Iain Knight, Martin Dodd, Alix Edwards, Mervyn Edwards, Phil Martin and Mike McCarthy
ESV 19-0315	Assessing the case for requiring AEB on city buses and developing technical requirements and test procedures (2019). Iain Knight, Martin Dodd and Alix Edwards
PPR872	Bus Safety Standard: Executive Summary (2018). TfL & TRL
PPR819	Analysis of bus collisions and identification of countermeasures (2018). Alix Edwards, Adam Barrow, Siobhan O'Connell, Varun Krsihnamurthy, Rahul Khatry, Nicola Hylands, Mike McCarthy, Shaun Helman and Iain Knight

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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