Advanced Driver-Assistance Systems for City Bus Applications

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Abstract

The bus sector is currently lagging behind when it comes to implementing autonomous systems for improved vehicle safety. However, in cities such as London, public transport strategies are changing, with requirements being made for advanced driver-assistance systems (ADAS) on buses. This study discusses the adoption of ADAS systems within the bus sector. A review of the on-road ADAS bus trials shows that passive forward collision warning (FCW) and intelligent speed assistance (ISA) systems have been successful in reducing the number of imminent pedestrian/vehicle collision events and improving speed limit compliance, respectively. Bus accident statistics for Great Britain have shown that pedestrians account for 82% of all fatalities, with three quarters occurring with frontal bus impacts. These statistics suggest that the bus forward collision warning system is a priority for inclusion in future vehicles to enhance the driver's direct vision, and to increase reaction time for earlier brake application. Almost 80% of bus occupant casualties occurred in non-impact situations, mainly during acceleration/deceleration events. Therefore, care must be taken in implementing autonomous braking in buses, to ensure that it does not cause an increased number of deceleration events beyond the safe stability limits for passengers. Real on-road drive cycle data has shown that while instances of unsafe braking events do not occur regularly, there are instances of braking events that would present a hazard to both seated and standing passengers, therefore systems that would mitigate these issues would have real benefits to both passenger comfort and safety. During tests to simulate the use of the vehicle retarder for an autonomous braking system, deceleration rates largely remained safely within standee and seated passenger stability limits, whereas an emergency stop test showed a peak deceleration 3.5 times the limit of a standee supported by a vertical handrail, and 4 times the limit for a forward/backward facing seated passenger.

Introduction

Major advances in safety innovations have been made in recent years in the automotive sector, resulting in advanced technology and driver assist systems becoming more widely available. An advanced driver-assistance system (ADAS) can be defined as a vehicle-based intelligent safety system which could improve road safety in terms of crash avoidance, crash severity mitigation and protection during post-crash phases [1]. A recent report by the Society of Motor Manufacturers and Traders (SMMT) and JATO dynamics [2] shows that 66.8% of all new cars in the UK are offered with at least one self-activating safety system, either as standard or as an optional extra. The most common ADAS systems found in vehicles in the automotive sector include collision warning systems, autonomous emergency braking (AEB), parking assist, and active cruise control (ACC). A study conducted by KPMG and SMMT in 2015 lead to estimations that by the year 2030, the application of autonomy to vehicles could prevent more than 25,000 serious accidents, saving over 2,500 lives in the UK [3]. Fildes et al. [4] conducted a meta-analysis using data from real-world crash events which showed that low speed AEB technology, such as that in a city application, is effective in reducing front-to-rear end collisions by 38%. Cicchino [5] compared collision statistics from two Volvo vehicles, a saloon and an SUV, equipped with AEB systems, to similar vehicles without the system. The study showed that the AEB system reduced front-to-rear crash rates and injuries by 43% and 45% respectively. When combined with a forward collision warning system (FCW) the front-to-rear crash rates were reduced further to 50%, and front-to-rear injury crash rates to 56%. A study conducted by the AAA Foundation for Traffic Safety [6] determined that FCW/AEB systems have the potential to prevent approximately 14% of all motor vehicle crash fatalities. The European Commission are currently considering an updated proposal to the current regulations [7, 8], that govern active and passive safety measures for all vehicles sold in Europe, which have fallen behind the technical advances. The new proposal would require for all new car types to come equipped with 11 mandated safety features from 2021, which includes AEB, drowsiness and attention detection, intelligent speed assistance (ISA), reversing camera or detection system, and lane keep assist, to name a few [9].

Although ADAS systems are common place on cars nowadays, there is a lag in the technology availability within the bus sector. In 2017/18 there were 4.85 billion local bus passenger journeys in Great Britain (GB), representing over 59% of all public transport journeys covering 16.9 billion passenger miles [10]. In the same time period, there were over 1,700 fatalities on Great Britain roads in 2017, with a further 25,000 people seriously injured [10]. Buses and coaches were involved in 3% of those killed or seriously injured (KSI) casualties.

However, public transport strategies are changing. In the city of London, in the Mayor of London's Vision Zero transport strategy there is an ambition to achieve zero deaths or serious injuries on London roads by 2041, with no one killed on, or by, a London bus by 2030. Transport for London have developed a Bus Safety Standard, under which all new bus designs for London will be assessed [11]. As well as assessing new vehicles on occupant friendly interior and vulnerable road user (VRU) frontal crashworthiness, the standard also has a roadmap for the requirement of ADAS systems. Intelligent Speed Assistance (ISA) is a requirement as early as mid-2019. Currently Advanced Emergency Braking (AEB) is set to be mandatory from 2024. Other ADAS requirements which will be gradually phased in include camera monitoring systems, pedal application error and runaway bus prevention. At the moment, there are no requirements for retrofitting of ADAS systems to buses currently in service.

It is in this context that the current study will discuss the adoption of ADAS systems within the bus sector, overviewing the various collision warning and ISA ADAS trials that have been conducted on buses and documented in literature to date. It will also discuss ADAS ergonomics, and acceleration/deceleration limits that must be considered when applying an autonomous braking system. Accident data will be used in order to show the main types of accident that could benefit from ADAS utilisation. The results of an on-road trial, conducted by the authors, using the bus retarder to simulate the functionality of an ISA or AEB system as an alternative to the service brakes will be presented and discussed. This work was undertaken at the Sir William Wright Technology Centre at Queen's University Belfast in conjunction with the bus manufacturer Wrightbus [12-16].

Literature Review

Collision Warning Advanced Driver-Assistance Systems

Mobileye Shield+ is a collision avoidance warning system that has been specifically developed for transit buses [17]. The system includes four cameras; one forward facing camera on the bus windshield, one covering the blind spot created by the A-pillar, and external forward facing cameras on each side of the bus towards the rear which cover the blind zones behind the driver. The system, which has been trained to detect vehicles and vulnerable road users (namely pedestrians and cyclists), provides coverage of the blind zones that are hidden from the driver's view, alerting the driver to avoid potential collisions. Indicators placed on the left and right A-pillars of the windshield flash yellow if a pedestrian or cyclist is identified to be within 2.5 seconds or less of colliding with the bus, or red with an audible alarm if the collision is within 1 second. An indicator mounted in the centre of the windshield provides forward collision warning, indicating the distance to the vehicle in front, lane departure warning and speed limit violation warning. This system can be optimised to cover the specific blind zones of the operator.

One of the most notable on-road trials of a bus ADAS system was that conducted by the Transit IDEA (Innovations Deserving Exploratory Analysis) Program [17]. In this project, the Mobileye Shield+ system was piloted on a fleet of 35 buses operating across the state of Washington, USA, for a period of three months. The buses fitted with the system logged a total of almost 24,000 operating hours, and covered a distance of over 350,000 miles. The system was operated in two conditions – 33 buses had fully active systems on-board, providing visual/audible alerts to the driver, and 2 were operated in stealth mode (detection systems on but no providing the visual/audible alerts). The two buses operating in stealth mode covered 17,000 miles during the trial period and transmitted collision warning data via telematics only for later analysis and performance benchmarking. During this trial, none of the buses equipped with the active Mobileye Shield+ system were involved in any collisions with pedestrians or cyclists, while those operating in "stealth" mode had six collisions with cyclists, three with pedestrians and one with a motorcycle. On the buses with the system active, alerting the driver of impending collisions, there were 71.6% fewer forward collision warnings and 43.3% fewer pedestrian collision warnings per 1000 miles than for the buses with the system in "stealth" mode. The results of the pilot showed how the active collision warning system was successful in improving the safety of the vehicle, with the drivers appearing to drive more safely, with less near miss collisions.

However, even though the testing showed that the system resulted in improved safety, a survey completed by the drivers showed that only 37% felt that the system was helpful, with only 33% indicating that they would like to drive with the system active in their bus. This was largely attributed to the occurrence of false positive alerts, particularly when the bus was turning in towards the footpath at a bus stop. The trial found that 3.2% of the alerts were false positives, identifying an area that needs improvement within the system. The bus operator Abellio London, conducted a trial of Mobileye Shield+ on 66 buses across 3 of their London bus routes. Preliminary results have shown that the technology has reduced the number of avoidable collisions and injuries by 29% and 60%, respectively [18].

A study by Thompson et al. [19] at Transport for New South Wales undertook a trial of Mobileye 560 on a fleet of 34 government vehicles for a period of seven months. The trial was conducted with the system initially in "stealth" mode with no alerts, then with active alerts, and finally with the system in "stealth" mode again in order to determine if the system had a lasting effect on driving behaviour. With the alerts active, there was a statistically significant reduction in headway and lane departure warnings, with drivers increasing their following distance, drifting out of lane less and increased use of indicators. However, these driving improvements were not maintained when the alerts were later deactivated. Similar to the findings of the Transit IDEA project, a survey of drivers participating in the Transport for New South Wales study showed that they preferred to drive without the system due to distraction from the alerts, but did recognise that it helped them to drive more safely. In this trial, around 25% of forward collision warnings were found to be false positives. In China, a study was conducted by Lyu et al. [20], in order to determine the effect that Mobileye M630 had on the driving performance and braking behaviour of 32 car drivers. The ADAS system was shown to have a significant effect on braking behaviour, with drivers tending to increase braking time and reducing relative speeds. The occurrences of deceleration rates less than $-3.0\ m/s^2$, $-3.5\ m/s^2$ and $-4.0\ m/s^2$ reduced by 12.5%, 14.3% and 50.0% respectively. The ADAS system also resulted in reductions in headways of less than 0.5s, 0.4s and 0.3s by 36.6%, 44.4% and 100% respectively. Bella et al. [21] at Roma TRE University conducted a driving simulator study of a pedestrian collision warning system which featured visual, audible and haptic warnings for the driver. The ADAS system trialled on the simulator was shown to improve driving behaviour, with increased driver reaction to pedestrians resulting in braking manoeuvres being conducted at a greater distance from the pedestrian, with reduced deceleration rates.

It is clear from all of the trials conducted on the collision warning systems that it has a positive effect on driving safety. Utilisation of the systems was shown to reduce collision near misses, increased headway to the vehicle in front, improved lane keeping, and increased braking times.

Intelligent Speed Assistance

Research conducted at the Transport Research Laboratory by Taylor et al. [22] has shown that a reduction in the average vehicle speed by 1 mph could reduce the accident frequency on busy town roads by around 6%. The ability to limit the vehicle to the speed limit of the road on which it is travelling will go some way to lowering the average speed, and therefore potentially reducing the accident frequency. Intelligent speed assistance (ISA) can autonomously maintain the vehicle below the road speed limit. Existing systems, such as the previously discussed Mobileye Shield+ system is capable of warning the driver that the speed limit has been exceeded by using street sign recognition to determine speed limit of the road. However, this system does not actively keep the vehicle below the limit. In 2015, Transport for London conducted a trial of an ISA technology across two London bus routes in order to provide an understanding of the potential role of the technology in promoting adherence to speed limits across the road network [23]. The ISA technology used in the trial was an intervening type system, which used GPS data matched against an on-board map and speed limit database to electronically prevent the equipped vehicles from exceeding the speed limit by controlling the amount of acceleration that was possible. The system was not able to actively apply the brakes. The technology was shown to be very effective in 20 mph speed zones, with the percentage of time the buses spent travelling above the speed limit reduced from a range of 14.9-17.8% to 1.0-3.3%. In 30 mph speed zones, where the typical driving speeds were generally well below the speed limit, the percentage of time buses spent travelling above the speed limit reduced from a range of 0.5-3.3% to 0.0-1.1%. Within the 20 mph speed zones, the average speed of the buses equipped with ISA reduced by more than 1 mph, from 17.88 mph to 16.79 mph. Passengers showed no awareness of the technology. However overall journey times increased slightly by 1.4%.

Passenger Stability

Although widely available in cars, AEB systems (which automatically applies the vehicles brakes in order to prevent or reduce the severity of an impending collision) have not been utilised in the bus industry due to stability concerns for unrestrained passengers. For autonomous braking to be applied for ISA or active collision mitigation ADAS systems, considerations must be made for safe braking limits. Kirchner et al. [24] acknowledges the fact that the majority of bus passenger injuries occur due to non-collision situations, such as braking and accelerating to/from a bus stop. The authors [24] conducted a study in order to understand the acceleration and deceleration profiles of such manoeuvres under real-world driving conditions. For buses approaching a bus stop, the average maximum deceleration was found to be 1.9 m/s^2, with an event duration of 9.8 seconds. The average duration of a bus pulling accelerating away from a bus stop was calculated to be 13.6 seconds, with a peak acceleration of 1.5 m/s^2. Whilst conducting a study to examine the effect of longitudinal vehicle acceleration on passenger safety and comfort, Powell et al. [25] discusses the experiments conducted by Hirshfeld [26] while designing the PCC streetcar in the USA. Hirshfeld found that on average the unsupported standees would lose their balance at 1.6 m/s^2, increasing to 2.3 m/s^2 when supported by an overhead strap, and 2.6 m/s^2 with a vertical grab rail. Based on experimental studies, as well as passenger surveys and observations, Hoberock [27] determined a limit for acceptable non-emergency accelerations in the range of 1.1 m/s^2 to 1.5 m/s^2, with a jerk limit of 2.94 m/s^3. From experiments aimed at determining the maximum deceleration that will allow the average unrestrained transit passengers to remain securely seated, Abernethy [28] suggested a limit of 2.45 m/s^2 for forward/backward facing passengers, and 1.4 m/s^2 for side facing passengers. During the tests conducted by Powell et al. [25] on the Tyne and Wear Metro, the authors routinely observed accelerations approaching 1.4 m/s^2, which was found to be acceptable. The authors also state that the guidelines of 1.1-1.5 m/s^2 suggested by Hoberock are reasonable.

Ergonomics

Automation of buses is occurring at a much slower rate to that of cars. When carrying a large number of passengers, whose safety is considered as a priority to bus operators [29], it is important to understand when applying ADAS how both the driver and the passengers will react to the autonomous technology. Research conducted at the University of Southampton has warned against a driver relinquishing the monitoring of the driving environment task to the vehicle, and being expected to regain control as a fall-back, such as in SAE Automation Level 3 [30]. Banks et al. [31] states that it is reasonable to suggest that a driver will engage in a secondary task if the driving task is relinquished to automation, and that a driver's reaction time to an unexpected hazard will increase by 1-1.5 seconds compared to when they are in control of the driving task. This was found to be applicable for an ADAS system such as adaptive cruise control. Eriksson [32] found that the time required for a driver to resume control of a vehicle increases from a minimum of 1.97 seconds, when a driver is monitoring the driving environment, to a minimum of 3.17 seconds when performing a secondary task. It is suggested that the driver should always have at least one of longitudinal or lateral control, or be completely removed entirely from the control-feedback loop (SAE Level 4) where the driver is not required to regain control of the vehicle [33].

In some cases the step has been taken to apply fully autonomous buses to a controlled environment, such as that under the CityMobil2 project in La Rochelle, France [34]. In this project an Automated Road Transport System was demonstrated, which consisted of a fleet of six automated buses, each with a carrying capacity of 10 passengers. The buses were each equipped with GPS for localisation, and radar and laser for object detection, and operated along a 1.4 km route and six bus stops. According to a survey conducted during this project, around two thirds of the public surveyed would consider taking automated buses if both automated and conventional buses were available on a route. However, passenger security was deemed as a concern to the public due to the absence of a driver, especially during night time services.

Bus operators understand that introduction of ADAS technology is an important factor in improving bus safety [29]. However it is obvious from this literature review that careful consideration of many factors is required, both technically and psychologically.

GB Bus Accident Statistics

In order to improve the safety of buses, it is first of all important to understand the most common factors that contribute to collisions and injuries. This information can then be used in order to choose the most suitable ADAS systems for prevention. In this study road accident data for Great Britain between the years of 2011 and 2017, provided by the Department for Transport, was analysed [35]. This data is made up of police reported traffic accidents that include an injury to at least one person. As the data is from police-reported collisions it does not include minor incidents that may only be reported to insurers. However, for bus accidents under-reporting issues should be minimal. The database contains approximately 50 pieces of information for each accident that has taken place, detailing fields such as the vehicle types involved, casualty types and severity, and vehicle impact point. For this study the data was filtered down to accidents that only involved buses. From the data the injuries in accidents involving buses to pedestrians, bus and coach passengers, and car passengers were examined, the totals of which are shown in

Table 1. Over the period of 2011-2017, it can be seen that pedestrians suffered the significant majority of fatalities at 82%. Only seven car passengers were killed due to a collision with a bus over the time period studied. This number is thought to be small due to the nature of city bus operation mainly within 20-30 mph speed zones, and therefore the majority of collisions would be expected to occur with both vehicles travelling at relatively low speeds.

Table 1. Pedestrians, bus passengers, and car passengers injured due to accidents involving buses in Great Britain from 2011-2017.

	No. Casualties				
	Slight	Serious	Fatal	% of Total KSI	% of Total Fatalities
Pedestrians	5520	1551	196	51%	82%
Bus Passengers	21352	1558	37	47%	15%
Car Passengers	1245	48	7	2%	3%
Total	28117	3157	240		

Pedestrian Casualties

Between 2011 and 2017 there were 196 reported deaths of pedestrians in accidents involving buses, with a further 1,551 seriously injured. For each of these pedestrian casualties, the relative motion of the pedestrian and bus vehicle were examined in more detail, including analysis of the manoeuvre that the bus was performing and the first point of impact between the bus and the pedestrian.

Figure 1 shows the breakdown of locations of pedestrians involved in a fatal collision with a bus, and Figure 2 further explores the activity being carried out by the pedestrians during these fatal events. 77% of pedestrian fatalities involving bus vehicles occur during road crossings, with at least 53% occurring during illegal crossings away from a designated pedestrian crossing facility. Over half of these fatalities occurred with the pedestrian crossing from the nearside of the bus, where the driver has a reduced reaction time. Figure 3 and Figure 4 show the breakdown of bus manoeuvres and impact positions, respectively, in collisions that resulted in pedestrian deaths. It can be seen from these statistics that most of the pedestrian fatalities occurred when the bus was moving straight ahead, with only 17% during turning manoeuvres. Three quarters of the vehicle-pedestrian impacts occurred at the front of the bus, where the driver has direct vision. These statistics suggest that the bus forward collision warning system is a priority for inclusion in future vehicles to enhance the driver's direct vision, and to increase reaction time for earlier brake application.

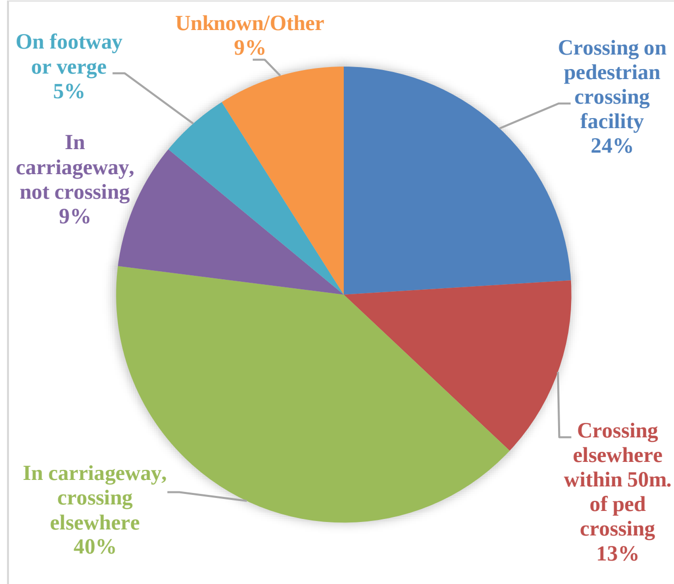

Figure 1. Percentage of pedestrian fatalities by location in accidents involving buses in Great Britain between 2011 and 2017.

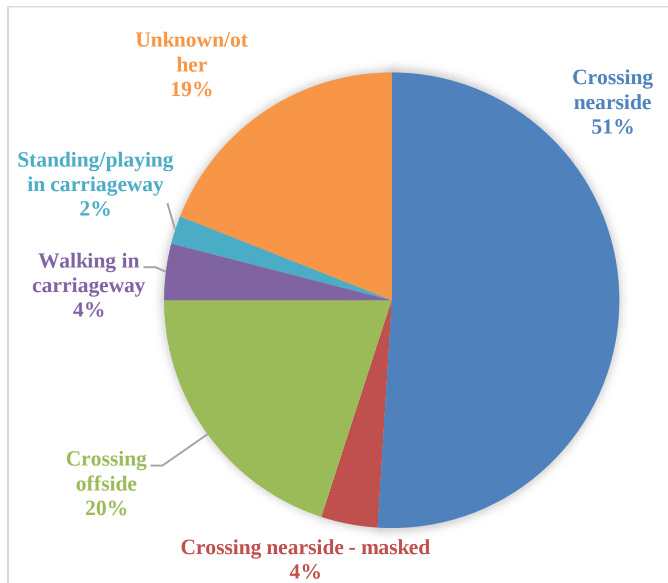

Figure 2. Percentage of pedestrian fatalities by pedestrian relative motion in accidents involving buses in Great Britain between 2011 and 2017.

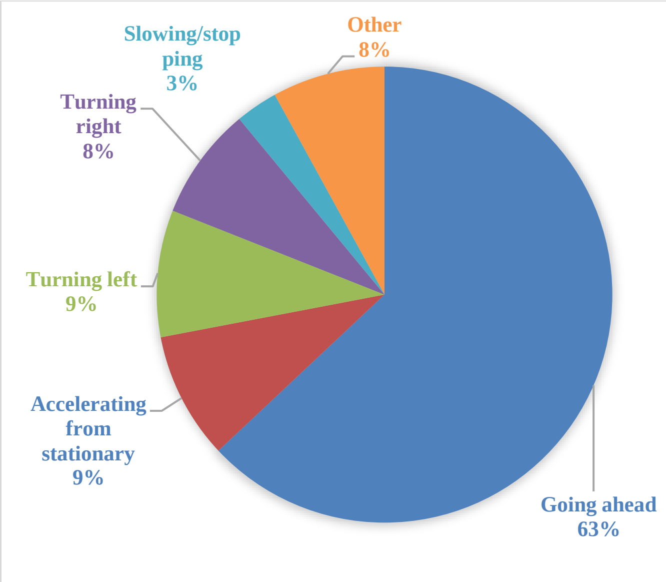

Figure 3. Percentage of pedestrian fatalities by bus manoeuvre in accidents involving buses in Great Britain between 2011 and 2017.

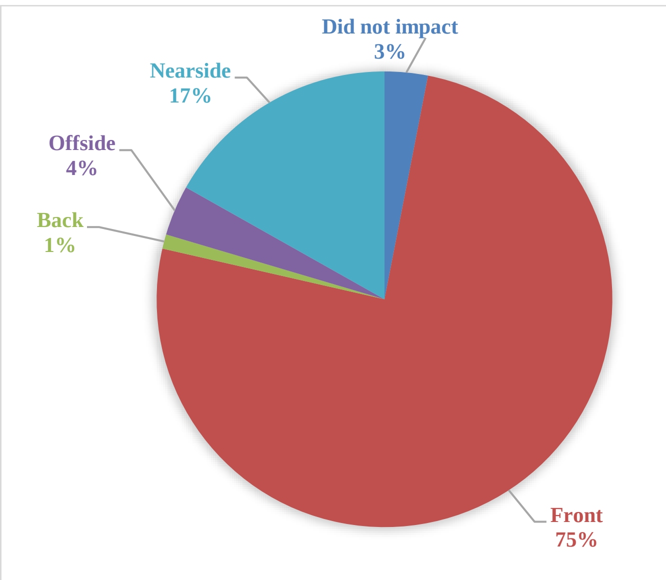

Figure 4. Percentage of pedestrian fatalities by pedestrian-bus impact point in accidents involving buses in Great Britain between 2011 and 2017.

Car Passenger Casualties

Car occupants accounted for only 2% of all fatalities or serious injuries in accidents analysed between the years of 2011 and 2017, as shown in Table 1. In terms of those car passengers killed or seriously injured, over 80% occurred due to collisions with the front of the bus, as shown in Figure 5, again where the driver has direct vision. There are instances of car occupant fatalities and KSI casualties caused by buses, where the bus did not come into impact with the car, but there may have been some other impact with the car. An example of this may be a car colliding with other vehicles and/or stationary objects due to a lane change manoeuvre conducted in an attempt to avoid a collision with a bus. Figure 6 shows the manoeuvre being conducted by the bus during the bus-car collisions that result in car occupant KSI casualties. A combined 14% of these occurred while the bus was slowing down or accelerating from stationary, which may be while approaching and leaving bus stops. The majority of the collisions occurred while the bus was travelling straight ahead, as shown in Figure 6. Yet again, it appears that a forward collision warning system in order to enhance the direct vision of the driver may be the most suitable ADAS system in order to reduce bus collisions with other vehicles on the road.

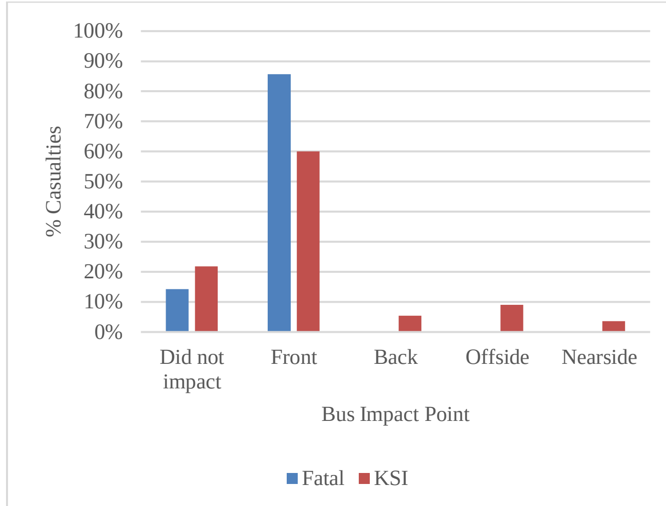

Figure 5. Percentage of car occupant fatalities and KSI casualties by bus-car impact point in accidents involving buses in Great Britain between 2011 and 2017.

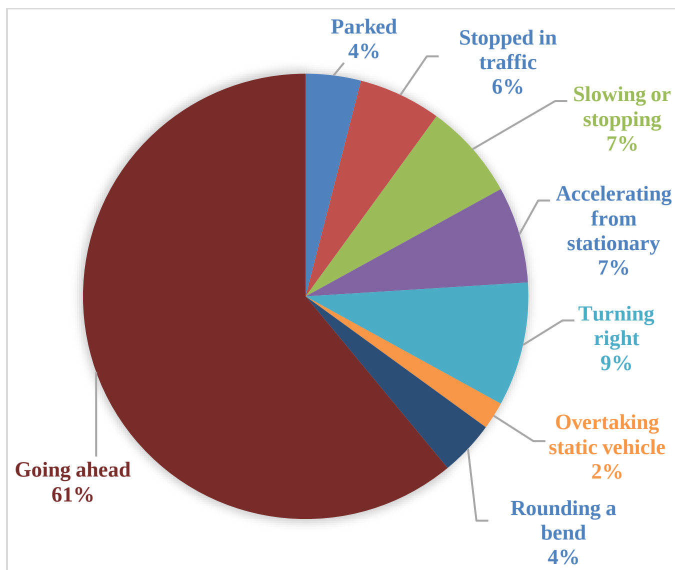

Figure 6. Percentage of car occupant KSI casualties by bus manoeuvre in accidents involving buses in Great Britain between 2011 and 2017.

Bus Occupant Casualties

The data analysed in this study has shown that during the years of 2011 to 2017 there were 37 people killed on-board buses in Great Britain. These statistics for bus occupants were broken down into passenger involvement, as shown in Table 2, and it was found that 16 of these fatalities were standing passengers, and 15 were seated.

Further analysis into impact position of the bus with other vehicles shows that almost 80% of bus occupant fatalities, and 80% of KSI casualties occurred in non-impact situations, as shown in Table 3. Figure 7 shows the percentage of fatalities of the standing passengers compared to seated passengers for each of the bus manoeuvres being conducted, that resulted in death. In the case of standing passengers it was observed that a total of 50% of fatalities occurred during the deceleration events of slowing or stopping, and accelerating from stationary. It can be assumed that these were non-impact situations where the passengers may have lost their balance. For seated passengers, the percentage of deaths during these acceleration and deceleration events was only 20%, with the majority occurring while the bus was moving ahead at speed. In total, 11 of the 31 deaths (35%) to standing and seated bus occupants occurred during the acceleration and deceleration events. When applying ISA and active collision avoidance ADAS systems to city bus applications these statistics must be considered. If autonomous application of the brakes leads to increased frequency of deceleration (and subsequent acceleration) events, the number of KSI casualties for bus occupants may increase further. On the other hand, the application of a collision warning system that increases driver awareness may result in safer braking, with improved stopping distances and longer forward headway (as has been shown in literature), should reduce these KSI casualties.

Table 2. Breakdown of bus occupant involvement casualties due to accidents involving buses in Great Britain from 2011-2017.

Passenger Involvement	No. Casualties Serious	Fatal	% of Total KSI	% of Total Fatalities
Boarding	140	4	9%	11%
Alighting	164	2	10%	5%
Standing passenger	668	16	43%	43%
Seated passenger	586	15	38%	41%
Total	1558	37		

Table 3. Impact position of bus for bus occupant casualties due to accidents involving buses in Great Britain from 2011-2017.

Impact Position	Serious	Fatal	% of Total KSI	% of Total Fatalities
Did not impact	1246	29	80%	78%
Front	182	3	12%	8%
Back	26	1	1%	3%
Offside	16	0	1%	0%
Nearside	86	4	6%	11%
Total	1556	37		

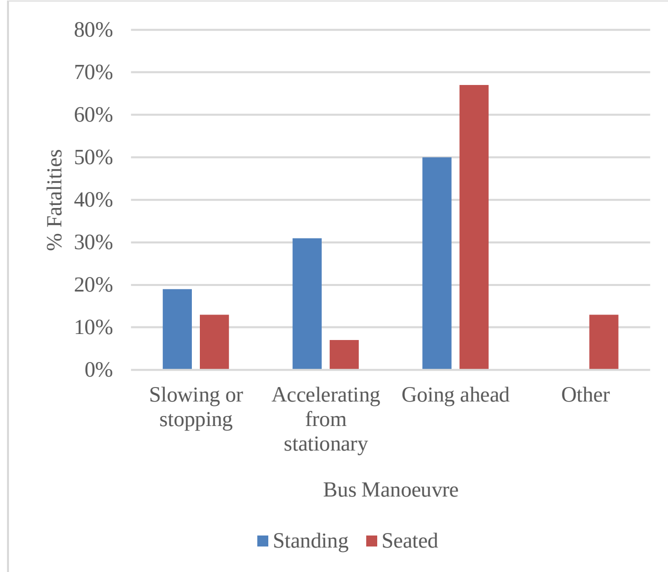

Figure 7. Percentage of bus occupant fatalities for standing passengers compared to seated passengers for different bus manoeuvres, in Great Britain between 2011 and 2017.

Bus Drive Cycle Analysis

When considering the implementation of safety systems which impose some level of deceleration on the vehicle, it is useful to understand the typical deceleration characteristics under normal operation. By performing data logging on real world bus drive cycles, it is possible to analyse the acceleration/deceleration profiles of buses on a typical city bus route. This study uses data logged on-board a double deck Wrightbus StreetDeck bus, servicing a UK-based route with mixed inner city and urban roadways during the period of 1st August to 30th October 2018. 687 drive cycles were extracted from the data set (all with a driven distance of greater than 5 miles), resulting in 1,015,226 individual acceleration/deceleration events recorded in 1 second time steps, equating to around 282 hours of driving. Figure 8 shows the distribution of the acceleration/ deceleration events recorded throughout all of the drive cycles logged (0 m/s^2 events removed for clarity). Analysis of this data has shown that 0.24% (2,471 individual events) of the acceleration/deceleration events recorded exceeded the -1.5 m/s^2 stability limit for unsupported standees on board a bus.

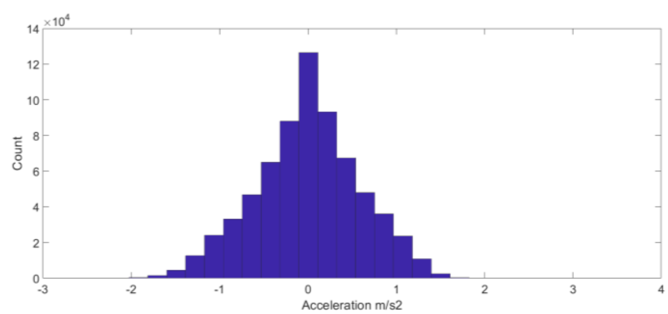

Figure 8. Distribution of acceleration/deceleration events for all of the drive cycles conducted on a double deck bus, in the UK, on a single route between 1st August and 30th October 2018.

The data shows two instances where the bus experienced decelerations below -2.5 m/s^2. The full drive cycle in which one of these excessive deceleration events occurred is shown in Figure 9. Figure 10 shows the velocity and deceleration profile for one of the specific events. The glyphs plotted on Figure 10, at 1 second intervals, illustrate the occasions when the deceleration was lower than -1.5 m/s^2, which was observed to occur for a period of 5 seconds. The orange glyphs represent deceleration rates below -1.5 m/s^2, and the red represent decelerations below -2 m/s^2. The unsafe deceleration event can be seen below the stability limit line for unsupported standing passengers at -1.5 m/s^2, which is plotted as a red dashed line. In this braking event, which appears to be an emergency braking manoeuvre, the vehicle was brought to a halt from almost 30 mph (45 kph). It can be seen from Figure 10 that there is a lag of around 1 second between the initiation of the deceleration event and transition to the full emergency braking event. The deceleration peaks below -2.5 m/s^2, which is beyond the stability limit for both unsupported standees and those holding an overhead strap, and is close to the limit for those passengers holding a vertical handrail [26, 27]. The peak deceleration is also beyond the recommended stability limit suggested by Abernethy [28] for both forward/rear facing seated passengers and sideways facing seated passengers. This manoeuvre therefore was clearly of danger to both standing and seated passengers on board the bus.

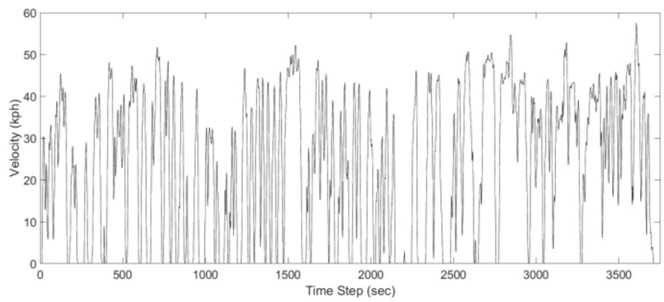

Figure 9. Drive cycle for a double deck bus in the UK during which there was a hazardous deceleration manoeuvre.

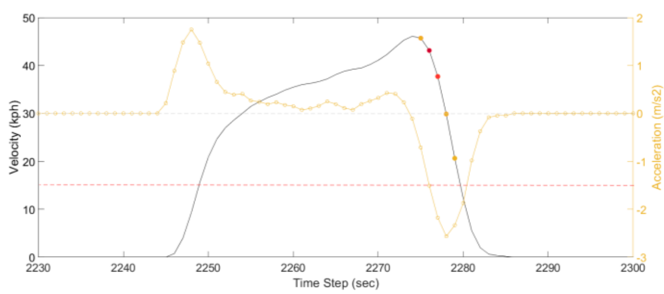

Figure 10. Velocity and acceleration/deceleration profiles for a hazardous braking manoeuvre for a double deck bus on a UK bus route.

This real on-road drive cycle data has shown that while instances of unsafe braking events do not occur regularly, there are instances of braking events that would present a hazard to both seated and standing passengers, and therefore systems that would mitigate these issues would have real benefits to both passenger comfort and safety. There are multiple ways in which braking can be achieved in the vehicle, and in the follow up tests, the use of the retarder in the vehicle to control the rate of deceleration in the vehicle was examined to identify its' viability as an alternative to the vehicle service brakes.

Retarder Testing

As was found from the analysis of accident statistics, a large proportion of bus occupant fatalities occur during acceleration and deceleration events. With ISA and AEB systems due to become a requirement for buses in the coming years, it is important to consider the technology that will be used to achieve these requirements in order to autonomously brake the vehicle without causing increased injury to unrestrained passengers, particularly standees. Systems trialled on buses to date have not actively applied the brakes, but have instead limited the acceleration available to the driver.

In this study, on-road testing was conducted which applied the vehicle retarder, rather than the service brakes, in order to decelerate a Wrightbus StreetDeck bus, with 4 passengers on-board, including the driver. This vehicle has a passenger capacity of 73 seated and 27 standees, with a sub 11,000 kg unladen weight [36]. The bus was almost unladen during the tests conducted. Typically, the retarder is used in heavy duty vehicles in order to maintain a steady speed while travelling downhill, and to reduce the use of the service brakes for increased lifetime. The testing was conducted in such a way as to attempt to simulate the functionality of an ISA or AEB system, with the accelerator being cut and the retarder applied. This testing was conducted in order to investigate the deceleration profiles produced by retarder application, and to allow comparisons to be made between the peak deceleration rates and the stability limits of standing and seated passengers discussed in the literature. Retarder application was conducted at speeds of 20 mph and 30 mph, as these are the speed zones in which city buses across the UK are to primarily operate. These speeds also reflect global urban maximum speed limits for city centre operation. The testing conducted aims to represent buses that will be operating within city and town centres, carrying both standing and seated passengers, rather than coach/Greyhound services that operate on intercity/interstate routes with higher speed limits.

Initial tests were conducted to decelerate the bus from a constant speed of 20 mph. The testing was conducted on a straight, flat, isolated road. The bus was brought to a constant speed of 20 mph, at which point the driver removed their foot from the accelerator pedal and the retarder was applied with a 10% braking torque. The percentage braking torque was requested from the retarder by a TSC1 signal sent from a laptop computer. Effectively, the brake pedal was replaced in the tests by a software brake. When the bus had decelerated to a speed of around 5 mph the retarder was deactivated and the driver drove the bus back to the original location for the next test to be conducted. Further tests were conducted from 20 mph with retarder braking torque requests of 20%, 30%, 50%, 70% and 100%. CAN data was logged throughout the testing, at a frequency of 100 Hz, using a DEWESoft DS-Net data logger. The data extracted included the wheel based vehicle speed, the retarder percentage torque and the engaged gear. The results of retarder braking from 20 mph are shown in Table 4, with the average deceleration rate from 20 mph to 10 mph displayed, along with peak deceleration. Figure 11 shows the deceleration profiles for each of the manoeuvres conducted.

Table 4. Peak deceleration and average deceleration from 20-10 mph for varying percentages of retarder application.

Retarder Brake Torque	10%	20%	30%	50%	70%	100%
Peak Deceleration (m/s^2)	-0.93	-1.04	-1.36	-1.55	-1.46	-1.52
Av Deceleration 20-10 mph (m/s^2)	-0.56	-0.74	-0.88	-0.98	-0.95	-0.97

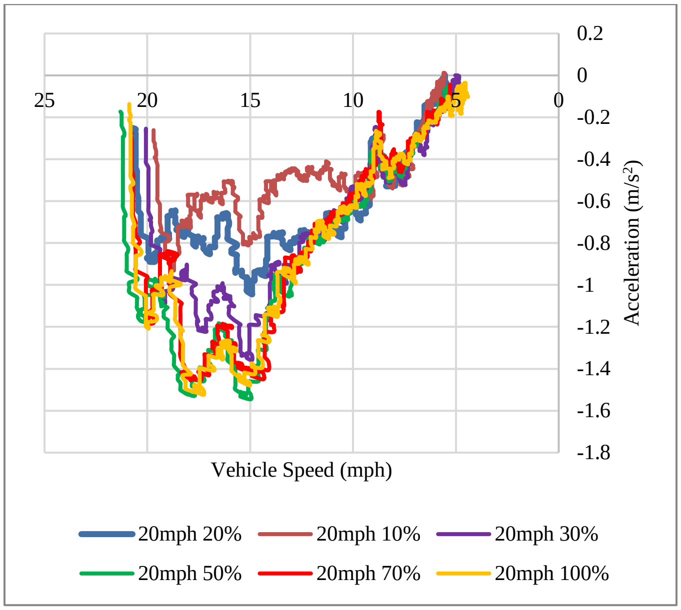

Figure 11. Deceleration profiles for varying retarder percentage brake torque application at 20 mph.

It can be seen from Table 4 that as the requested retarder brake torque increases so too does the peak deceleration, up until 50% retarder brake torque. This trend can be seen on Figure 11. From 50-100% requested retarder brake torque the deceleration profiles are very similar, with average deceleration (from 20-10 mph) and peak decelerations experienced almost identical. The deceleration peaks at $-1.55\ m/s^2$, which lies just beyond the limits of -1.1 and $-1.5\ m/s^s$ for unsupported standees suggested by Hirshfeld [26] and Hoberock [27], but well within the comfortable limits of $-2.3\ m/s^2$ and $-2.6\ m/s^2$ for standees with an overhead strap and vertical handrail for stability, respectively, and also well within the limit of $-2.45\ m/s^2$ for forward/back facing seated passengers suggested by Abernethy [28]. The average deceleration for all of the testing scenarios was also well within the comfortable limits. The maximum average and peak deceleration was found to occur at 50% retarder application. As only one test was conducted at each retarder setting, further testing would be required in order to examine if this is a repeatable trend. These results show that there would be no safety issue involved with autonomous application of 0-100% retarder at 20 mph. The tests show that there is no added benefit of increasing the retarder demand beyond 50% brake torque.

The next tests conducted simulated the bus decelerating from a 30 mph speed limit. The procedure was the same as that for the 20 mph tests. From the initial testing, conducted at 20 mph, the peak deceleration rates were found to occur from 50% retarder application and above. Therefore, testing was conducted for retarder braking torques of 50%, 75% and 100%, decelerating the bus from 30 mph. Table 5 shows the results of the testing at 30 mph, with the peak deceleration, average deceleration when slowing from 30 mph to 20 mph, and the average deceleration between 30 mph and 10 mph. Each of the deceleration profiles, for 50%, 75% and 100% retarder brake torque application, are plotted in Figure 12.

Table 5. Peak deceleration and average decelerations from 30-20 mph, and 30-10 mph, for varying percentages of retarder application.

Retarder Brake Torque	50%	75%	100%
Peak Deceleration (m/s^2)	-1.75	-1.71	-1.87
Av Deceleration 30-20 mph (m/s^2)	-1.10	-1.19	-1.20
Av Deceleration 30-10 mph (m/s^2)	-1.08	-1.12	-1.10

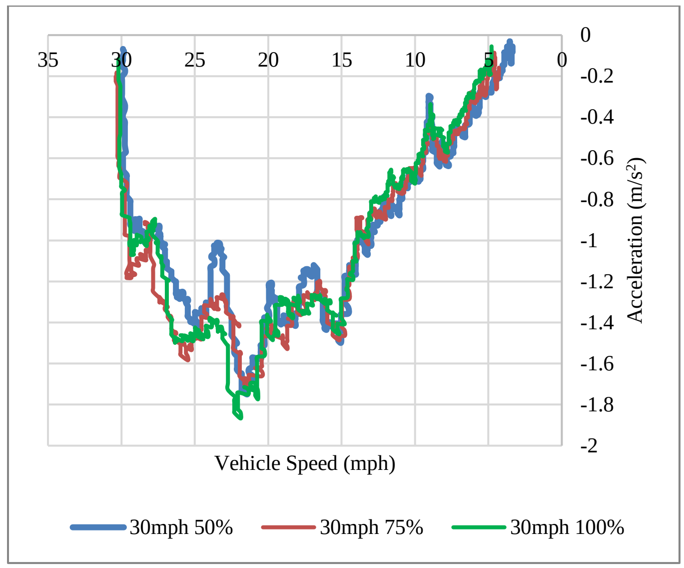

Figure 12. Deceleration profiles for varying retarder percentage brake torque application at 30 mph.

It can be seen from Figure 12 that each of the deceleration profiles are very similar. As shown in Table 5, the highest peak deceleration and highest average deceleration from 30-20 mph occurred with 100% brake torque application of the retarder, with values of -1.87 m/s^s and $-1.20\ m/s^s$ respectively. Deceleration rates of below $-1.8\ m/s^s$ were only experienced for a time period of 0.12 seconds during the braking manoeuvre. The peak deceleration reached was beyond the -1.5 m/s^s limit for unsupported standees suggested by Hirshfeld [26] and Hoberock [27], but only for a time period of 0.64 seconds. The average and peak decelerations for all test scenarios were well within the comfortable limits of $-2.3\ m/s^2$ and $-2.6\ m/s^2$ for standees with an overhead strap and vertical handrail for stability, respectively, and also well within the limit of $-2.45\ m/s^2$ for forward/back facing seated passengers suggested by Abernethy [28]. The three passengers on-board the vehicle found that they were comfortably able to stand unsupported without losing balance during all retarder tests conducted. These results show that if the retarder is to be applied, even at 100%, and throttle cut from a speed of 30 mph, the deceleration rate will remain within comfortable limits. Again, there is little to no advantage of operating the retarder beyond 50% brake torque. The tests show that the retarder may be an acceptable alternative to the service brakes for AEB/ISA systems, acting as a stopgap technology while active AEB/ISA braking systems using the service brakes are developed. Assuming linear extrapolation, it has been calculated that 42 mph is the hypothetical maximum speed at which 100% retarder application would result in deceleration rates within the safe limit of -2.3 m/s^2 for standing passengers supported by overhead straps.

An emergency stop was conducted in order to observe the deceleration rate that would be caused by actively applying the bus service brakes. An emergency stop is effectively the event that would be conducted by a collision avoidance system with active AEB. The test was conducted on a Wrightbus StreetDeck with only 10 occupants on-board, in order to achieve near worst case (maximum) deceleration. The driver conducted an emergency stop by applying the brakes at around 40 mph. This speed was chosen for the test in order to simulate an extreme event, at the upper limit of daily city bus operation. Data from this manoeuvre was also logged using the DEWESoft DS-Net data logger. The vehicle speed and acceleration are plotted in Figure 13. This braking event occurred over a time of almost 4 seconds. The deceleration peaked at -9.6 m/s^2, which is more than five times the peak deceleration that occurred during the retarder testing. In fact, this peak deceleration was over 3.5 times the limit for the stability of a standing passenger with the support of a vertical handrail as suggested by Hirshfeld [26], and almost 4 times the acceptable limit for the stability of a forward/backward facing passenger suggested by Abernethy [28]. If this type of manoeuvre was to be performed autonomously, and unexpectedly to the drivers and passengers, it is a certainty that significant injury could occur to both standees and seated occupants.

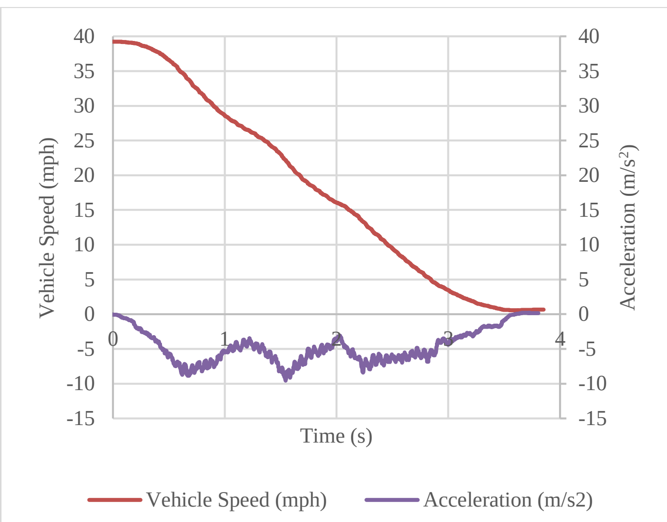

Figure 13. Vehicle speed and deceleration profiles for an emergency stop on a Wrightbus StreetDeck.

The deceleration profiles presented in this study were all obtained from the testing of a Wrightbus StreetDeck, double deck bus. However, the results of the testing should be comparable to other double deck buses operating within a city/urban environment, with a similar gross vehicle weight (18,000 kg), which have retarders installed directly to the transmission and are compliant with braking regulations for operation in the UK.

Summary/Conclusions

Autonomous systems are common place nowadays, with most new cars introduced onto our roads featuring at least one ADAS system, in an effort to reduce avoidable collisions. However, it can be seen that ADAS is not widely utilised in the bus sector. This is changing in cities such as London, which is becoming more aware of safety on public transport. All new buses in London will be assessed based on a Bus Safety Standard which has been introduced by Transport for London. The Bus Safety Standard has a requirement for ISA and AEB systems to be installed on buses by 2019 and 2024, respectively. Trials of ADAS systems on buses have been limited, with the majority of testing being conducted on passive collision warning technology such as Mobileye Shield+. This system has proved to have been successful in reducing the number of imminent collision events with pedestrians and other vehicles. The literature also described the testing of a GPS based ISA system, which was shown to be very effective at keeping the bus below the speed limit in 20 mph zones.

In this study analysis of accidents in Great Britain (GB) between the years of 2011 and 2017 was conducted. While this is a GB based case study, it is applicable to other regions of the world where there is increasing interest in the application of ADAS systems for city bus operation. As the operational context in GB is similar to other regions globally, the findings of this work will be applicable to other big cities, such as New York or Hong Kong. The results have shown that pedestrians account for the majority of fatalities in accidents that involved buses. This was mainly due to illegal crossing from the nearside of the bus, where the driver has a reduced reaction time. Collisions with both pedestrians and vehicles mainly occurred with the front of the bus, where the driver has direct vision. These statistics suggest that forward collision warning ADAS is a priority for future buses. For bus occupants it was found that 80% of fatalities and KSI casualties occurred in non-impact situations, with 50% of passenger deaths occurring during acceleration and deceleration manoeuvres. It is clear from these statistics that serious consideration is required for the application of autonomous braking to buses in any ISA/AEB systems being proposed. The literature has shown safe stability limits of -1.5 m/s^2 to -2.6 m/s^2 for standing passengers and -1.4 m/s^2 to -2.45 m/s^2 for seated passengers.

Analysis of the drive cycles conducted by a double deck bus servicing a route in the UK, for mixed inner city and urban roadways, has shown that instances of unsafe braking events are rare. However, on board the particular bus studied, there were observed to be two emergency braking manoeuvres during the monitoring period. During one of these events the deceleration exceeded -1.5 m/s^2 for a period of 5 seconds and was seen to peak beyond -2.5 m/s^2, a rate that is hazardous to both standees and seated passengers. There was also observed to be a lag between the initiation of the deceleration event and transition to the full emergency braking event. This data shows the need for an automated system that will improve this reaction time, observing potential collisions earlier, allowing for a less severe braking event to be conducted.

It may be possible that the vehicle retarder be used as an alternative, or stopgap, while a safe system for use of the service brakes for active AEB/ISA systems in buses is developed. In this study testing was conducted on an unladen WrightBus StreetDeck bus in order to determine the deceleration profile during retarder application. During the testing the deceleration was shown to peak at -1.87 m/s^s, however, during this event the deceleration only exceeded the -1.5 m/s^2 stability limit for unsupported standees for a period of 0.64

seconds. The average decelerations that occurred during the retarder braking events were always safely within the stability limits for both supported standing and seated passengers.

An emergency stop event was conducted in order to determine the deceleration rate that occurred when the bus brakes were applied suddenly, as in the case of an AEB event. During this test the deceleration peaked at -9.6 m/s^2, which was more than five times the peak deceleration that occurred during retarder testing. The peak deceleration was over 3.5 times the comfortable stability limit for standee with a vertical handrail, and almost 4 times the comfortable stability limit for forward/backward facing seated passengers. If an event such as this was to occur unexpectedly to the driver and pedestrians, it is expected that significant injury would be suffered by both standees and seated passengers.

In future work further testing will be conducted with retarder application at the upper speed limits of city bus operation. Also, use of the service brakes for AEB at lower speed limits of 20-30 mph shall be conducted. It will then be important for a prototype active ISA/AEB system to be developed and a trial be conducted on a test bus operating on a test track.

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Definitions/Abbreviations

ACC	Active cruise control
ADAS	Advanced driver-assistance system
AEB	Autonomous emergency braking
FCW	Forward collision warning
ISA	Intelligent speed assistance
KSI	Killed or seriously injured
VRU	Vulnerable road users