THE FUTURE
OF TRANSPORT

PUBLISHED PROJECT REPORT PPR991

The Transport for London (TfL) Bus Safety Standard: Acoustic Conspicuity

Evaluation of Safety Measure

Phil Morgan, Alix Edwards, Mike Ainge, David Jenkins,
Stephen Skippon, Phil Martin, Mike McCarthy

Report details

Report prepared for:	Transport for London (TfL)		
Project/customer reference:	tfl_scp_001593		
Copyright:	© TRL Limited		
Report date:	December 2018		
Report status/version:	Version 1.0		
Quality approval:			
Anna George (Project Manager)		Mike McCarthy (Technical Reviewer)	

Disclaimer

This report has been produced by TRL Limited (TRL) under a contract with Transport for London (TfL). Any views expressed in this report are not necessarily those of Transport for London (TfL).

The information contained herein is the property of TRL Limited and does not necessarily reflect the views or policies of the customer for whom this report was prepared. Whilst every effort has been made to ensure that the matter presented in this report is relevant, accurate and up-to-date, TRL Limited cannot accept any liability for any error or omission, or reliance on part or all of the content in another context.

When purchased in hard copy, this publication is printed on paper that is FSC (Forest Stewardship Council) and TCF (Totally Chlorine Free) registered.

Executive Summary

Bus Safety Standard (BSS)

The Bus Safety Standard (BSS) is focussed on vehicle design and safety system performance and their contribution to the Mayor of London's Transport Strategy. This sets a target to achieve zero road collision deaths involving buses in London by 2030, and zero Killed and Seriously Injured (KSI) casualties by 2041 for all vehicles including buses.

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

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

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

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

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

Acoustic Conspicuity

An Acoustic Vehicle Alerting System (AVAS) is a system to make quiet running (e.g. electric, hybrid-electric, and hydrogen) buses as identifiable to pedestrians, and other road users outside the vehicle, as a standard diesel bus. This is intended to help Vulnerable Road Users (VRUs) detect the presence of a bus and the collision risk it represents if they were to cross in front of it.

Regulation will require that electric and hybrid buses are fitted with AVAS on new models from July 2019, and on all new builds from 2021. TfL is mirroring the regulatory requirements but has chosen to implement them sooner, subject to legal review.

The current sounds that are being used are developed by motor manufacturers to reflect their individual brand and vehicle characteristics. The technology can be transferred to buses (Category M3) provided an appropriate sound is developed to characterise a unique larger vehicle. TfL is investigating the development of an “urban bus” sound. The aim of this is to harmonise the AVAS sounds across London's bus fleet, regardless of which company has manufactured the bus, thereby minimising the number of new sounds introduced into an already very busy and noisy environment, and avoid the risk of confusing VRUs.

An evaluation procedure has been developed to assess solutions and aid the design/selection of the urban bus sound. Testing has shown that a front mounted AVAS could increase detection distance by approximately 5 times compared to a rear mounted diesel engine bus. The results of the benefits-cost analysis indicate a positive benefit-cost ratio over the 12-year period (2019 – 2031).

Table of Contents

Executive Summary ii

Bus Safety Standard (BSS) ii

Acoustic Conspicuity iii

1 Introduction to the Bus Safety Standard (BSS) 1

1.1 The BSS 1

1.2 Bus safety measures 2

1.3 Acoustic Conspicuity 3

2 Defining the problem 5

2.1 Casualty priorities for TfL 5

2.2 The casualty problem for acoustic conspicuity 5

3 System definition 9

3.1 System performance 9

4 Existing standards and test procedures and their suitability for buses. 12

4.1 UNECE Regulation 138 14

4.2 BS ISO 16254:2016 14

4.3 SAE J2889TM-1 (November 2015) 15

4.4 FMVSS 141 15

4.5 Recommendations 16

5 AVAS sound development 17

5.1 Considerations for AVAS sound development 17

6 Development testing of an AVAS sound for the BSS 21

6.1 Trackside evaluation 21

7 Benefit-costs analysis 28

7.1 Target population 28

7.2 Estimates of effectiveness 29

7.3 Implementation and fleet fitment timescales 29

7.4 Casualty benefits 30

7.5 Cost implications 31

7.6 Benefit-cost analysis outcomes 33

8 Conclusions and next steps 34

9 References 35

10 Acknowledgements 37

Appendix A Glossary of abbreviations and acronyms 38

Appendix B Glossary of acoustic terms and symbols 39

Appendix C Vehicle type approval 40

Appendix D Details of proposed test programme for evaluation and selection of an AVAS sound for BSS 42

Appendix E Questions raised during the research 44

Appendix F General cost-benefit analysis approach 47

1 Introduction to the Bus Safety Standard (BSS)

1.1 The BSS

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

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

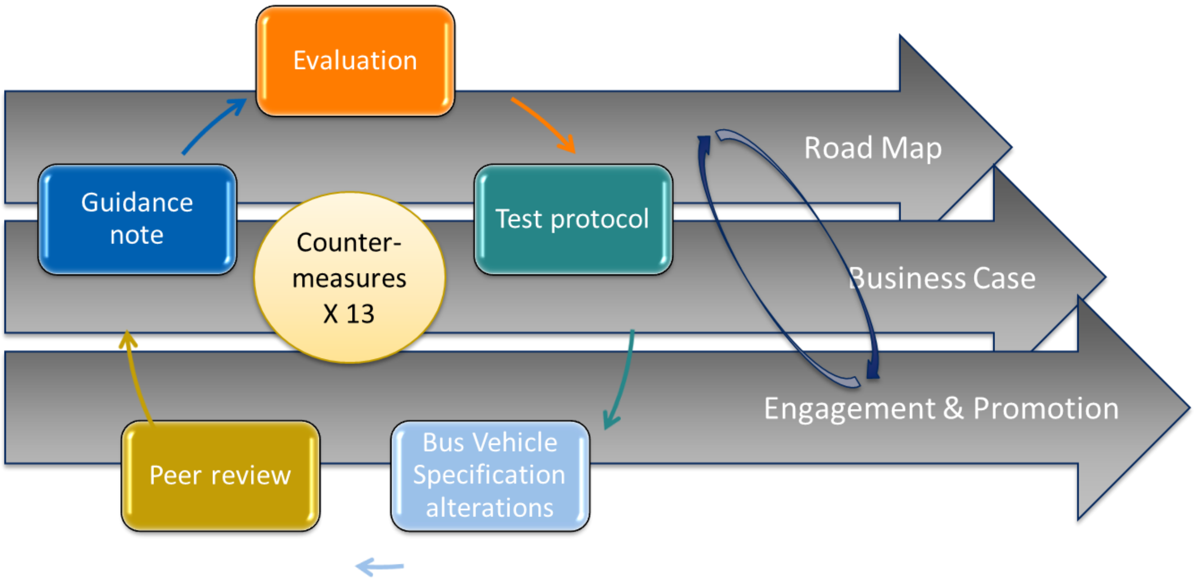


Figure 1-1-1: Summary of the BSS research programme

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

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

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

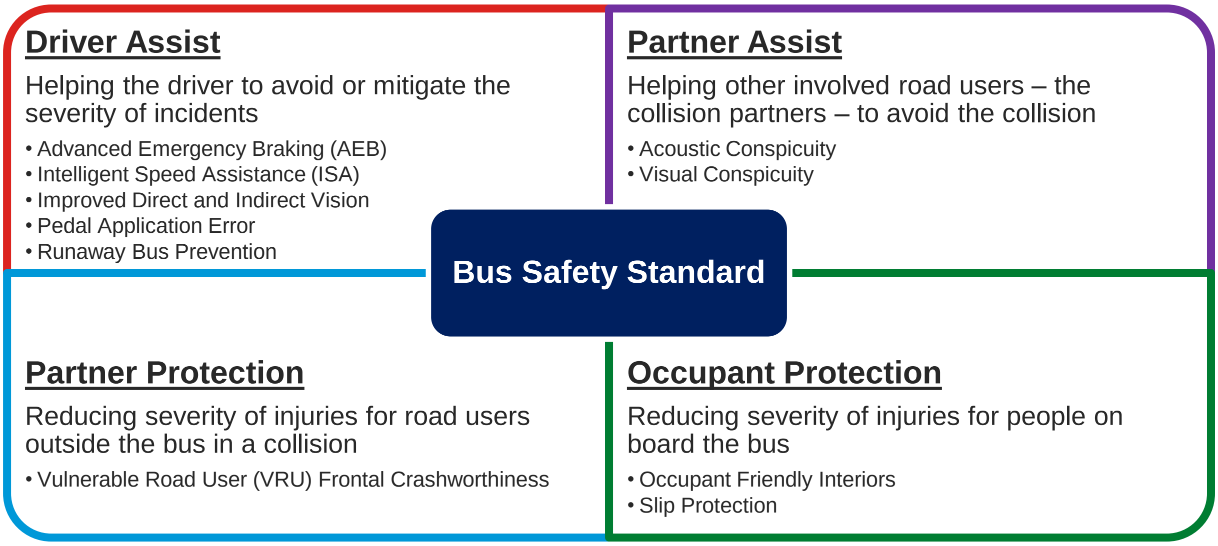
It is important to ensure the money is spent wisely on the package of measures that will give the most cost-effective result. If zero fatalities can be achieved at a low cost, it remains better than achieving it at a higher cost. TRL has developed a cost-benefit model describing the value of implementing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

1.2 Bus safety measures

The measures selected for consideration in the BSS were wide ranging, as shown in Figure 1-1-2. Some will address the most frequent fatalities, which are the group of pedestrians and cyclists killed by buses, mostly whilst crossing the road in front of the bus. There are several measures that could address this problem, for example, Advanced Emergency Braking (AEB, which will apply the vehicle’s brakes automatically if the driver is unresponsive to a collision threat with a pedestrian) or improved direct and indirection vision for the driver. These are both driver assis safety measures, which are designed to help the driver avoid or mitigate the severity of incidents. Intelligent Speed Assistance (ISA) is another example of driver assist, and TfL has already started rolling this out on their fleet. The last two driver assist measures are pedal application error (where the driver mistakenly presses the accelerator instead of the brake) and runaway bus prevention; both of which are very rare but carry a high risk of severe outcomes.

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

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



Driver Assist

Helping the driver to avoid or mitigate the severity of incidents

- Advanced Emergency Braking (AEB)
- Intelligent Speed Assistance (ISA)
- Improved Direct and Indirect Vision
- Pedal Application Error
- Runaway Bus Prevention

Partner Assist

Helping other involved road users – the collision partners – to avoid the collision

- Acoustic Conspicuity
- Visual Conspicuity

Bus Safety Standard

Partner Protection

Reducing severity of injuries for road users outside the bus in a collision

- Vulnerable Road User (VRU) Frontal Crashworthiness

Occupant Protection

Reducing severity of injuries for people on board the bus

- Occupant Friendly Interiors
- Slip Protection

Figure 1-1-2: Bus safety measures

1.3 Acoustic Conspicuity

The term acoustic conspicuity has been used in connection with quiet vehicles, i.e. vehicles with alternative propulsion systems that exhibit less noise than a conventional internal combustion engine (ICE), such as an electric (EV), hybrid electric (HEV), or hydrogen drivetrains[1]. The term can be broken down into the definition of each of the two words, which are given in the English Oxford Dictionary (Anon., 2018) as:

- **Acoustic**: Relating to sound or the sense of hearing; (of building materials) used for soundproofing or modifying sound, e.g. 'acoustic tiles'; (of a device or system) utilizing sound energy in its operation.
- **Conspicuity**: Clearly visible; attracting notice or attention.

Therefore, in simple terms, acoustic conspicuity relates to using sound to make an object more noticeable and by association, more visible.

In the context of the Transport for London (TfL) Bus Safety Standard (BSS) the focus is on what can be achieved with respect to acoustic conspicuity for the new fleet of buses with EV and HEV drivetrains that TfL has purchased and is proposed to continue purchasing over the coming years.

There is a concern that the number of collisions between Vulnerable Road Users (VRUs) and quiet buses travelling at low speed could increase because of the lack of low speed noise cues. However, it is also true that, many collisions have occurred

---

[1] The drivetrain is defined as being the group of components that deliver power to the driving wheels of a vehicle. Note: this excludes the engine or motor that generates the power.

where a pedestrian has failed to correctly observe and judge the collision risk associated with an approaching diesel bus.

Therefore, achieving the *equivalent acoustic conspicuity* of a conventional diesel bus is only a part of the solution, and it may be necessary to develop solutions that actually *increase acoustic conspicuity* compared to a conventional diesel bus.

Both can only be done by adding sound to a quiet bus via an Acoustic Vehicle Alerting System (AVAS); these were originally developed for electric and hybrid electric cars. The technology and concepts are suitable for use on buses as the goals are still the same, namely:

- To create a sound that is identifiable by a wide range of the population.
- To create a sound that meets the current regulations on minimum sound.
- To create a sound that is not annoying or irritating to the majority of the population where the vehicles are used.
- To create a sound that can be easily distinguished from other sounds, such as background sounds and other traffic.

There is already a European Directive and a number of associated standards to control the development and use of AVAS on cars, buses and trucks. This will require that AVAS be fitted on all new EV and HEV bus models (new designs requiring type approval) from July 2019 and on all newly registered vehicles with these drivetrains from September 2021.

A key point in developing an AVAS is that consideration must be given to ensuring that any solution is not detrimental to the environmental noise experience by everyone who lives and works in a city.

This report sets out the steps to define a solution for this issue.

2 Defining the problem

2.1 Casualty priorities for TfL

Transport for London’s aim in implementing the bus safety standard is to assist in achieving ‘vision zero’ on the principle that no loss of life is acceptable or inevitable. Thus, the largest focus is on incidents resulting in death or serious injury. However, they recognise the disruption and cost that minor collisions can have for bus operators and the travelling public alike. Thus, safety features that can reduce the high frequencies of incidents of damage only and/or minor injury are also included within the scope. The high-level matrix below in Table2-1 categorises and prioritises the casualties based on past data for London derived from the GB National collision database.

Table 2-1 shows that over the past decade the highest priority casualty group in terms of death and serious injury from collisions involving buses in London has been pedestrians severely injured in collisions where the bus was coded as going ahead, without negotiating a bend, overtaking, starting or stopping, etc.

2.2 The casualty problem for acoustic conspicuity

New quieter buses are being introduced, with HEV, EV and hydrogen drivetrains. At speeds above around 20 mile/h tyre noise dominates the overall noise level from vehicles and at these speeds, such buses may emit noise levels that are not significantly different to conventional diesel buses.

However, at low speed the noise generated from the propulsion system is one of the important sources to alert pedestrians and vulnerable road users to the presence of a vehicle. Vehicles with these alternative drivetrains can be much quieter than conventional diesel buses. This removes one of the signals that pedestrians can use to identify the presence of a vehicle, its proximity and whether it is travelling at steady speed, accelerating or decelerating. This can be particularly relevant for blind or partially sighted road users that may rely on audible cues more than most of the population.

There is, therefore, a risk that the number of collisions between VRUs and buses travelling at low speed could increase because of the lack of low speed noise cues. However, it is also true that, as described for visual conspicuity, many collisions have occurred where a pedestrian has failed to correctly observe and judge the collision risk associated with an approaching diesel bus. Thus, achieving the *equivalent acoustic conspicuity* of a conventional diesel bus is only a part of the solution, and it may be necessary to develop solutions that actually *increase acoustic conspicuity* compared with a conventional diesel bus.

According to (Edwards *et al.*, 2017), of 48 police fatal collision reports involving London buses, 37 involved pedestrian fatalities, of which 30 occurred when a pedestrian was crossing the road in front of a bus.

Table2-1: Casualty prevention value attributed to different collision types; London STATS19 data from 2006-15 (%)

Casualty Type	Collision type	Fatal	Serious	Slight	KSI	Total
Bus Passenger	Injured in non-collision incidents - standing passenger	4.2%	17.1%	23.3%	11.9%	15.2%
	Injured in non-collision incidents - seated passenger	0.5%	6.4%	13.0%	4.0%	6.6%
	Injured in non-collision incidents - boarding/alighting/other	1.6%	7.6%	5.3%	5.2%	5.2%
	Injured in collision with a car	0.5%	4.6%	10.1%	2.9%	5.0%
	Injured in collision with another vehicle	0.0%	3.1%	5.0%	1.8%	2.8%
	Total	**6.9%**	**38.7%**	**56.7%**	**25.9%**	**34.8%**
Pedestrian	Injured in a collision while crossing the road with a bus travelling straight ahead	0.0%	1.5%	2.5%	0.9%	1.4%
	Injured in a collision, not while crossing the road, with a bus travelling straight ahead	0.0%	0.5%	0.5%	0.3%	0.4%
	Injured in a collision with a bus turning left or right	0.5%	1.2%	1.5%	1.0%	1.1%
	Injured in other collision with a bus	0.5%	3.2%	4.5%	2.1%	2.8%
	Total	**30.7%**	**20.0%**	**7.0%**	**24.3%**	**19.3%**
Car Occupant	Injured when front of bus hits front of car	10.6%	7.9%	4.6%	9.0%	7.7%
	Injured when front of bus hits rear of car	12.2%	3.1%	1.2%	6.8%	5.2%
	Injured when front of bus hits side of car	2.1%	1.4%	0.7%	1.7%	1.4%
	Injured in side impact collision with a bus	55.6%	32.5%	13.6%	41.8%	33.6%
	Injured in other collision with a bus	6.3%	1.9%	0.9%	3.7%	2.9%
	Total	**1.6%**	**0.8%**	**2.8%**	**1.1%**	**1.6%**
Cyclist	Injured in a collision with the front of a bus travelling straight ahead	1.1%	1.1%	1.8%	1.1%	1.3%
	Injured in a collision with another part of a bus travelling straight ahead	2.6%	1.9%	3.9%	2.2%	2.7%
	Injured in a collision with the nearside of a bus which is turning	2.1%	1.0%	1.4%	1.5%	1.4%
	Injured in other collision with a bus	13.8%	6.6%	10.8%	9.5%	9.9%
	Total	**2.1%**	**1.2%**	**0.9%**	**1.5%**	**1.4%**

Casualty Type	Collision type	Fatal	Serious	Slight	KSI	Total
Powered Two Wheeler (PTW)	Injured in a collision with a bus travelling straight ahead	0.0%	2.6%	1.5%	1.6%	1.6%
	Injured in a collision with a bus turning left or right	1.6%	0.8%	0.4%	1.1%	0.9%
	Injured in other collision with a bus	0.5%	3.1%	2.1%	2.1%	2.1%
	Total	**4.2%**	**7.8%**	**5.0%**	**6.4%**	**6.0%**
Bus Driver	Injured in collision with a car	2.6%	1.3%	0.7%	1.9%	1.5%
	Injured in non-collision incidents	0.5%	1.0%	0.7%	0.8%	0.8%
	Injured in collision with another vehicle	0.5%	1.0%	0.9%	0.8%	0.8%
	Total	**3.7%**	**3.4%**	**2.3%**	**3.5%**	**3.2%**
Other	**Total**	**15.3%**	**7.9%**	**7.1%**	**10.9%**	**9.8%**
Casualties Total		**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Audible cues such as engine noise can assist the pedestrian in deciding when to attempt crossing the road. However, most diesel buses have engines fitted to the rear of the bus; this provides a degree of masking to the sound generated by the engine, making it harder for the pedestrian to separate the engine sound from the background noise, limiting the effectiveness of the audible cue.

Electric buses do not have the same engine sound sources as diesel buses and can be quieter at low speed operation. Therefore, the audible cues pedestrians potentially use are either absent, or are lost in background noise (even more so than is the case for diesel buses).

From the work done on visual conspicuity, collisions appear to arise from three types of perceptual error on the part of the pedestrian:

- **Pedestrian not attending to the traffic situation**: In particular, not attending to the direction of oncoming traffic when beginning to cross a road. This is often attributed to distraction resulting from the use of mobile devices, particularly headphones and in-ear devices, or foreign tourists looking in the wrong direction, though in principle it could also be attributed to other sources of distraction such as interacting with other people.
- **Failure to identify oncoming vehicle**: Often referred to as ‘looked but failed to see’ (LBFTS), this refers to the situation where the pedestrian looks in the direction of oncoming traffic, but fails to identify the presence of a bus; it is a failure of search. It may be the result of insufficient search (e.g. cues are not distinguishable within a short duration to enable the scene to be fully processed so that object recognition is reliable) OR that the bus cannot be distinguished from the background sounds. While usually associated with visual search, it seems likely that audible cues will also help orient attention to the correct part of the scene.
- **Failure to estimate time to collision**: This refers to the situation where the pedestrian is aware of the presence of the bus but incorrectly estimates the time available to cross the road before it arrives (Time To Collision, TTC).

All three of these error types are potentially addressable through acoustic conspicuity measures to some degree. It might help to draw attention to the road, to identify the vehicle, and to help with estimating the time to collision (although there is less evidence for this last possibility). It can help to provide additional information that the pedestrian can interpret to enhance visual scanning of the scene.

Also, an NHTSA study by (Hanna, 2009) into HEV accident rates with pedestrians and cyclists found that on roads with low speed limits, during daytime and in clear weather, that there were higher incident rates for HEVs when compared to vehicles with an internal combustion engine (ICE).

In a specific group of scenarios when a vehicle was slowing or stopping, reversing, and entering or leaving a parking space, the study found that that a pedestrian was more than twice as likely to be involved in an incident with an HEV as with an ICE vehicle. The reason for this is potentially down to the scenarios being very low speed, where the difference in the sound level produced by a HEV and an ICE vehicle is the greatest.

3 System definition

A solution for increasing the acoustic conspicuity of vehicles with EV and HEV drivetrains has been defined as 'added sound’, or what is currently referred to as an Acoustic Vehicle Alerting System (AVAS). This is an audible warning that is active at low speed. Currently, systems are only active at speeds between 0 km/h to 30 km/h[2] inclusive, and are intended to replace engine noise as a cue to pedestrians and VRUs that a vehicle is approaching.

The speed at which the rolling noise (tyres, aerodynamics) becomes more dominant than the propulsion (engine, transmission) noise is called the cross-over speed; (Hammer *et al.*, 2016) conducted a study which defined the European vehicle fleet cross-over speed as 15.7 km/h. It used a combination of vehicle categories, namely diesel cars, petrol cars, diesel light-duty commercial vehicles, hybrid cars and electric cars to calculate the crossover speed. The purpose of the study was to investigate a more modern vehicle fleet to establish a model for present and future use.

The system generates a specific sound, (defined and developed by the OEM), created and projected from speakers at the front and rear of the vehicle, thereby giving an early warning to pedestrians that the vehicle is approaching. This system has been designed In order to improve pedestrian safety around electric and hybrid vehicles, by replacing the minimum noise generated by an ICE vehicle with artificial sound when an ICE drivetrain is absent, and to comply with governmental safety regulations.

3.1 System performance

The criteria for AVAS performance has been developed by two main streams of research and development.

One stream is within the development of Regulations and Standards for 'added sound', with research from the following organisations:

- **ISO (International Organization for Standardization)**: ISO is an independent, non-governmental international organization with a membership of 161 national standards bodies. Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges.
- **BSI (British Standards Institution)**: BSI is the national body responsible for preparing British Standards and other standards related publications, information and services.
- **UNECE (United Nations Economic Commission for Europe)**: UNECE was set up in 1947 by the United Nations Economic and Social Council (ECOSOC). It is one of five regional commissions of the United Nations.

---

[2] European and US Regulations determine the speed range at which an AVAS can operate.

UNECE's major aim is to promote pan-European economic integration. UNECE includes 56 member States in Europe, North America and Asia.

- **NHTSA (National Highway Traffic Safety Administration)**: NHTSA is responsible for keeping people safe on America’s roadways. Through enforcing vehicle performance standards and partnerships with state and local governments.
- **SAE International**: SAE, initially established as the Society of Automotive Engineers, is a U.S. based, globally active professional association and standards developing organization for engineering professionals in various industries. Principal emphasis is placed on connecting and educating engineers while promoting, developing and advancing aerospace, commercial vehicle and automotive engineering.

This includes their associated working groups such as the World Forum for the Harmonization of Vehicle Regulations (WP29) subsidiary body Working Party on Noise (GRB) and its informal group on Quiet Road Transport Vehicles (QRTV) which enable decision making for Regulations and Standards to be introduced.

The second stream is within the vehicle manufacturers themselves, using in house teams or in conjunction with industry specialists, to develop and test systems that comply with the Regulations and Standards as noted above. Vehicle manufacturers are an integral part of the process of developing Regulations and Standards, many as members of the associated working groups, and with some manufacturers publishing research to aid the discussion of the topic.

The performance of any AVAS can be classified in two ways:

- Does it fulfil the requirements of the relevant Regulations/Standards? These define performance based criteria where wording, limits and values must be adhered to.
- Can a vehicle requiring the AVAS be detected in the same way as a normal ICE vehicle?

(Kim *et al.*, 2012) found that the added sound will provide some benefit to blind pedestrians in particular. The study found that an HEV with an added artificially generated sound was detected at a distance of 38.3 m compared to the ICE version of the same vehicle which was detected at 34.5 m and an HEV without added sound which was detected at 27.5 m. Given that detecting an approaching vehicle at a sufficient distance is critical for the safety of blind pedestrians, equipping hybrid and electric vehicles with a sound system that emits an alerting sound under certain low-speed manoeuvre conditions may contribute to the safety of blind pedestrians.

It should be noted that any results for the detection of vehicles, with added sound or not will depend on a number of factors, including the following:

- The type of road surface.
- The output level of the AVAS.
- The distance from the vehicle.
- The background noise level.

It is important to remember that AVAS has been developed to replace the minimum noise generated by an ICE vehicle with artificial sounds when an ICE drivetrain is absent. There are now a number of vehicle manufacturers offering this type of system on their current electric vehicle models, including Renault, Audi, BMW, Jaguar, Nissan, GM and Chrysler. However, no such systems are currently commercially available for buses.

The number of AVAS systems in use raises confidence levels both in the current technology of 'added sounds' for electric vehicles and the potential suitability of the technology for use on buses; Section 6.1 gives further details on source position and source level.

3.1.1 Definition of vehicle categories

Vehicle categories used in the following text are defined according to the following classification, extracted from EU Directive 2007/46/EC (European Union, 2007) as last amended by Commission Regulation 385/2009 (European Union, 2009):

- **Category M**: Motor vehicles with at least four wheels designed and constructed for the carriage of passengers.
    - **Category M1**: Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat.
    - **Category M2**: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes.
    - **Category M3**: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes.
- **Category N**: Motor vehicles with at least four wheels designed and constructed for the carriage of goods.
    - **Category N1**: Vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes.
    - **Category N2**: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes.
    - **Category N3**: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tonnes.

Note: Category M3 vehicles would be typical of the bus fleet operating in London.

4 Existing standards and test procedures and their suitability for buses.

There are one Regulation and three main Standards that are currently available and which could be applicable to the development of acoustic conspicuity and AVAS for the BSS, as follows:

- **UNECE Regulation No 138 (October 2016)**. Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility (QRTV).

  Note: The UK is signed up to this Regulation in the UNECE Forum as a Contracting Party.

- **BS ISO 16254:2016**. Acoustics - Measurement of sound emitted by road vehicles of category M and N at standstill and low speed operation - Engineering method.
- **SAE J2889/1_201511 (November 2015)**. Measurement of minimum noise emitted by road vehicles.
- **FMVSS 141**. Minimum sound requirements for hybrid and electric vehicles.

The Standards and Regulation are all based on ISO 362-1 (ISO, 2015)/Regulation 51.03 (UNECE, 2016), which is currently used for the Type Approval Certification process for vehicles in category M and N, and they have been developed within the brief of '*what are the minimum sound levels that a low noise vehicle has to make to be comparable with a conventional ICE vehicle*'.

The Standards have been developed by the European Community (Regulation No. 138), UK (BSI), USA (SAE and FMVSS), and international cooperation (ISO), incorporating research and best practice. Table4-1 on the following page provides a summary of the main differences between the Standards; the following text provides more detail on the Regulation and each of the Standards and defines what it means to the development of the BSS. A glossary of relevant acoustic terms is included at the beginning of this report.

Table4-1: Summary of the main differences between the different Standards and Regulations

Main component	UNECE Reg138	BS ISO 16254:2016	SAE J2889/1	FMVSS 141
Applicable vehicle categories	M and N	M1, M2, M3,N1, N2, N3	M1, M2, M3,N1, N2, N3	M1, M2, N1 - Max limit of 4,536 kg due to limited information
Additional sound component	Sound component containing at least 2 of the one-third octave bands between 160 Hz and 5,000 Hz. At least one below and one within the 1,600 Hz band	Sound component containing multiple frequencies - then selected frequency to track for speed	Sound component containing multiple frequencies - then selected frequency to track for speed	Sound component have to meet a requirement specifying either two or four one-third octave bands. Vehicles complying with the four-band requirement must meet minimum sound pressure levels in any four non-adjacent one-third octave bands between 315 Hz and 5,000 Hz, including the one-third octave bands between 630 Hz and 1,600 Hz. Vehicles complying with the two-band requirement must meet minimum sound pressure levels in two non-adjacent one-third octave bands between 315 Hz and 3,150 Hz. For the two-band requirement, one band must be below 1,000 Hz and the second band must be at or above 1,000 Hz, and the two bands used to meet the two-band requirement also must meet a minimum band sum requirement.
Method to indicate speed (acceleration /deceleration)	Frequency shift by 0.8 % per 1km/h change of speed from 5 km/h to 20 km/h	Frequency shift by constant % per km/h change of speed	Frequency shift by constant % per km/h change of speed	Vehicle-emitted sound to increase in sound pressure level by a specified amount as the vehicle’s speed increases.
Method to indicate stationary vehicle (ready to move)	Option to have driver selected sound- criteria is the same as sound component	Not specified	Suggestion of a temporary increase in Sound Pressure Level (SPL) to create a commencing motion sound when the vehicle is ready to move	Minimum sound requirement when gear is selected and the vehicle is ready to move.
Max speed of measurements	20 km/h	10km/h or other speeds defined in regulations	20 km/h	30 km/h
Maximum overall sound level	75 dB(A)	Not specified	Not specified	Not specified

4.1 UNECE Regulation 138

The Regulation (UNECE, 2017) applies not only to vehicles with EV and HEV drivetrains, but also to those with fuel cell vehicle (FCV) drivetrains and fuel cell hybrid vehicle (FCHV) drivetrains, and to electrified vehicles (those with an electric motor powered from an external rail or catenary wire).

The Regulation defines an AVAS which is required to emit a constant noise at speeds between 0 and 20 km/h. This regulation has the most defined parameters when compared to BS ISO 16254 and SAE J2889/1, specifying (in Clause 6.2.1.2) that the sound shall contain at least two of the one-third octave bands between 160 Hz and 5,000 Hz; at least one of these one-third octave bands shall be below or within the 1,600 Hz band.

This is the only document that specifies a maximum overall sound pressure level (*SPL*); this begins to ensure that any added sounds don't become noisier than the ICE equivalent. It is also the only document that specifies the amount of frequency shift (0.8% per 1 km/h change of speed from 5 km/h to 20 km/h), ensuring a more constant tone with speed change. The frequency shift component is incorporated to signify acceleration and deceleration, and the intention of frequency shift is to acoustically inform road users about the change in vehicle speed.

It also has an option to have a driver selected sound when the vehicle is stationary, providing the sound complies with the criteria specified for the added sound component.

As with all of the Standards, there is a lot of scope to define what sound should be emitted and a manufacturer can develop its own unique sounds to identify with a particular product model and model year.

It should be noted that the UNECE website has now officially published the 01 series of amendments to UN Regulation No. 138. The main change is that this new amendment gives a clearer definition of the "pause function"[3] and prohibits its installation in a vehicle. This amendment entered into force on 10th October 2017.

It is anticipated that Regulation No. 138.01 will form a mandatory part of the EU type approval process from 1st July 2019.

4.2 BS ISO 16254:2016

This Standard (BSI, 2016) specifies an engineering method (i.e. how to) for measuring the sound emitted by M and N category vehicles at standstill and low speed operating conditions. The test method utilises the same acoustic environment as used for vehicle noise type approval purposes (see Appendix A), which can be

---

[3] The original iteration of Regulation 138 had a feature called a 'pause function' that enabled the AVAS to be switched off by the driver when the AVAS was deemed unnecessary. The subsequent 01 series of the Regulation removes this facility.

either an outside or inside facility. The method gives an objective measure of the sound emitted under the specified test conditions.

4.3 SAE J2889TM-1 (November 2015)

This SAE Standard (SAE, 2015) is derived from SAE J2805 and specifies an engineering method for measuring the sound emitted by M and N category road vehicles at standstill and low speed operating conditions.

The method is designed to meet the requirements of simplicity as far as they are consistent with reproducibility of results under the operating conditions of the vehicle. Again the test method utilises the same acoustic environment which is used for Type Approval purposes, which can be either an outside or inside facility.

Both BS ISO 16254 and SAE J2889/1 have similar technical requirements and use a frequency shift method for alerting vulnerable road users to the speed of the vehicle. SAE J2889/1 has a different overall test speed 20 km/h as opposed to 10 km/h and has the suggestion of a temporary increase in Sound Pressure Level (*SPL*) to create a commencing motion sound when the vehicle is ready to move.

4.4 FMVSS 141

This is the most comprehensive of the Standards reviewed; it has been developed by the National Highway Traffic Safety Administration (NHTSA) in the United States and includes comments from manufacturers and other stakeholders as well as the responses and decisions from NHTSA forming one of their Federal Motor Vehicle Safety Standards (FMVSS). This document (NHTSA, 2018)[4] differs slightly from the other two standards and Regulation and is the most recent. It also provides the research behind the decisions made.

Again, this document is similar to the others defining the methods and parameters to follow; there is a difference in the applicable vehicles the Standard is applied to, those being equivalent to M1, M2 and N1. It also specifies a maximum weight for applicable vehicles of 4,536 kg, and this is due to the limited information/research that was available on the noise generated by larger electric/hybrid vehicles and their diesel counterparts at the time of writing the Standard.

Originally the sound component was made of up to eight one-third octave bands; this has now been reduced to either two or four one-third octave bands.

- Vehicles complying with the four-band requirement must meet minimum sound pressure levels in any four non-adjacent one-third octave bands between 315 Hz and 5,000 Hz, including the one-third octave bands between 630 Hz and 1,600 Hz.
- Vehicles complying with the two-band requirement must meet minimum sound pressure levels in two non-adjacent one-third octave bands between 315 Hz

---

[4] The actual document reviewed was a pre-published final version (NHTSA, 2016). This document is now published, with minor amendments, as of 26th February 2018, becoming effective on 26 April 2018.

and 3,150 Hz. For the two-band requirement, one band must be below 1,000 Hz and the second band must be at or above 1,000 Hz, and the two bands used to meet the two-band requirement also must meet a minimum band sum[5] requirement.

This change is to make it easier to construct and test sounds while giving manufacturers the freedom to develop their own unique sounds.

A marked difference over the other Standards/Regulation is the method to acoustically identify when the vehicle is either accelerating or decelerating; the others use a frequency shift while this Standard uses the vehicle-emitted sound to increase in sound pressure level by a specified amount as the vehicle's speed increases or decreases. The overall speed that sounds must be generated and tested at is 30 km/h, the highest of all the Standards. This is based on the US research that was done as part of developing this Standard.

However, it should be noted that Honda reported that acoustic data shows a convergence of the vehicle's sound profiles between the engine-on and engine-off condition at 20 km/h, and that acoustic sound requirements at 20 km/h or more might not be necessary (NHTSA, 2016). Toyota also explained that data presented by the Quiet Road Transport Vehicles (QRTV) group have indicated that the appropriate crossover speed is 20 km/h, because tyre and wind noise exceed the noise of traditional ICE vehicle engines above this speed. Toyota mentioned that existing Japanese and European guidelines have adopted 20 km/h as the appropriate crossover speed and recommended that NHTSA do the same (NHTSA, 2016).

The vehicle weight restriction of this standard makes it unsuitable for use on buses used in London.

4.5 Recommendations

All of the Regulations/Standards reviewed above, except FMVSS 141, are applicable to use on buses in London, based on vehicle categories. Therefore, the reference Standard for testing and developing the additional sound for all EV, HEV and hydrogen vehicles of M and N categories should be Regulation 138; compliance with the regulation will make it easier for manufacturers to have a product that will be acceptable in many countries across the EU. The testing method in that Regulation should be followed when testing any electric or hybrid buses for use on the TfL network in the future.

---

[5] Band sum means the combination of Sound Pressure Levels (SPLs) from selected bands that produce an SPL representing the sound in all of these bands. (NHTSA, 2018)

5 AVAS sound development

At low vehicle speeds, tyre noise and aerodynamic noise is limited. For an ICE vehicle this results in a lower overall sound pressure level (*SPL*), however, there is still a significant level of noise emitted by the engine and drive train. For EVs, little noise is emitted by the electric motor; therefore, at low speeds the overall *SPL* emitted by these vehicles is minimal. AVAS is designed to give additional acoustic cues to VRU's to allow them to better recognise this new technology in the traffic stream.

5.1 Considerations for AVAS sound development

Most buses produced/used in the UK have the propulsion system at the rear of the vehicle, which may not be particularly audible to vulnerable road users even if the vehicle is a conventional diesel-powered bus.

Consideration should be given to whether the vehicle should replicate engine noise or something different, and whether a sound should be reproduced at the rear of the vehicle or introduce a sound source at the front of the vehicle, closer to the position of pedestrians and vulnerable road users at risk of collision with the bus.

Further developments of sound generations could be linked to other sensor systems. For example, the AVAS could be switched off when no vulnerable road users are ahead or alongside the vehicle to avoid nuisance noise. This could be enabled by suitable sensors around the vehicle such as those used in an Automated Emergency Braking (AEB) system. Warnings could be changed in intensity according to the proximity of the vulnerable road user or if they change trajectory from walking along the pavement to moving towards the edge of the pavement.

It will also be necessary to consider the fact that the subjective appraisal of the annoyance, perceptibility, and/or detectability of different motor vehicles or classes of motor vehicles due to their sound emission are not simply related to the indications of a sound measurement system. As annoyance, perceptibility, and/or detectability are strongly related to personal human perception, physiological human condition, culture, and environmental conditions.

To date, there is little direct research available that defines what an ideal 'sound' should be for an electric vehicle. Current standards allow for manufacturers to develop their own signature sounds for their vehicles that will be associated with a particular model. There are however, concepts that have been produced by FMVSS and motor vehicle manufacturers that indicate a direction to aim for, identifying key parameters that the added sounds should achieve; these are presented in Table 5-1.

Table 5-1: Key parameters for sound development

Key Parameter	Concept Requirement
Vehicle Presence	It should be possible to become aware of the presence of the vehicle by hearing it. In practice, it is unavoidable that there are situations in which the vehicle sound will be masked by other sounds.
Vehicle Identification	The vehicle should be recognizable as a vehicle by its sound: It should not be easily confused with other possible sound sources such as nature, people or fictional objects etc.
Vehicle Location	Other road users should be able to localize the vehicle and get a sense of its distance from their position.
Vehicle Direction	Other road users should be able to tell if the vehicle is coming towards the listener or if it is moving away.
Dynamic information	Based on the sound, it should be possible to get a sense of the speed of the vehicle and how this is changing: Is the vehicle accelerating strongly, decelerating or driving with a constant speed?
Legal Sound Requirements	Specific legal requirements that apply to these vehicles have to be taken into account in the sound design process, so they are included in the framework. Creating a sound that fulfils all regulations by designing for the strictest, most elaborate regulation will allow manufacturers flexibility in where they sell vehicles. A design of sound that fulfils the strictest requirements will also fulfil potentially looser requirements in a different region or country. However, until each country has finalised the rulemaking process, it can't be ruled out that regulations may contradict each other.

There is a second category of requirements that takes into account the real-world considerations of fitting vehicles with additional sound generators. These are broken down into three categories:

- **Acceptance**: A loud, piercing sound can be very effective in achieving the outlined functional requirements with the goal of maximum safety. In reality, such a sound is not desirable, practical or realistic.
- **Interior Comfort**: The purpose of the generated sound is to make other road users notice the electric vehicle emitting it, with the primary intent of increasing safety. Depending on the vehicle construction and the sound technology used, the sound may also be audible inside the vehicle. However, if the additional sound is more than "just audible" in the interior, it may negatively impact the interior comfort or even become an annoyance, as the sound exceeds the required or desired sound level for the people inside the vehicle.

  Maintaining the acoustic comfort inside the vehicle is therefore a target that should be taken into account in the sound design and development process by optimizing the frequency spectrum, focusing the acoustic energy into frequency areas that are known to be insulated well by the vehicle cabin. This will need the assistance of vehicle manufacturers to identify these areas.
- **Noise Pollution**: The contribution of each vehicle to the overall traffic noise and its effect on the environment needs to be considered as well (Konet *et al.*, 2011). Transportation vehicles are a primary contributor to noise pollution.

Adding sound to vehicles potentially increases traffic noise, so exceeding the necessary sound level or its intrusiveness should be avoided.

- **Spectral Composition**: The combination of legal, functional, aesthetic and technological requirements imposes many limits on the spectral composition of the sound. When visualizing BMW's experience with these limits in the frequency map shown in Figure 5-1 can provide insights that can help steer the sound design process (Vegt, 2016).

It should be noted that the graph lines and areas depicted are examples and approximations, which are strongly dependent on the vehicle geometry and construction, the AVAS hardware, its position in the vehicle and the sound. The graph shows the frequency areas that are impractical or unsuitable for real world quiet car sounds for consumer vehicles, and are identified by different types of shading. The areas highlighted in green are considered suitable frequency areas to be used for the sound design.

Taking into account the previous work done by vehicle manufacturers and Standards developers we can derive a best practice combination of sounds to make the 'added sound' as detectable as possible for use in the BSS.

The minimum requirements are listed in Table 5-2.

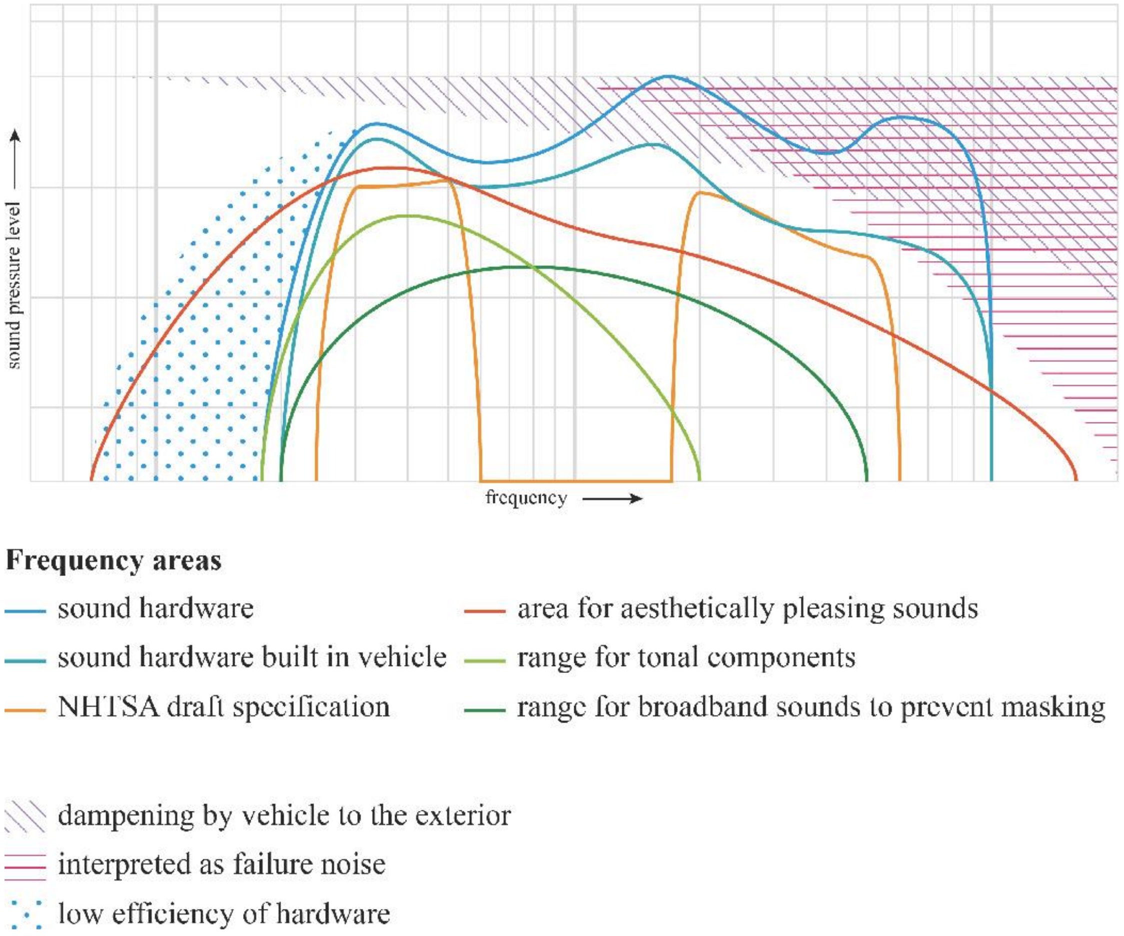


Figure 5-1: Concept of frequencies for added sound (from Vegt, 2016)

Table 5-2: Minimum requirements for added sound

Parameter	Minimum Requirement
Base sound	Manufacturer and TfL defined, currently an engine sound (Enviro 400)
Enhanced frequencies	1. Increase peak frequency content between 600 and 800 Hz to improve detectability for aging pedestrians with high Hz hearing loss. 2. Increase peak frequency content between 1600 and 2400 Hz to improve detectability for pedestrians with normal hearing. 3. Reduce frequency content at around 1000 Hz to avoid noise intrusion in neighbourhood communities and provide a quiet cabin.
Location of source	Two speakers located at the front of the vehicle, one on each side. The centre line of the speakers should be aligned towards the kerb side at an angle of 20º to 30º from the front surface of the bus.
Source directionally	120º to 140º
Speed range	O to 20kmh.
Accel/decel strategies	Frequency shift at 0.8%
Maximum level	75dB(A)

Parameter	Minimum Requirement
Legal compliance	Test to Regulation 138

6 Development testing of an AVAS sound for the BSS

A three-stage programme to evaluate and select an appropriate AVAS sound for use within the BSS was proposed, comprising the following:

- **Stage 1 – Laboratory based evaluation**: Subjective assessments of candidate sounds by research participants, ranked based on conspicuity and annoyance.
- **Stage 2 – Trackside evaluation**: Practical track tests using the five best ranked sounds from Stage 1; the objective is for research participants to confirm attention conspicuity (at what point the vehicle fitted with the AVAS becomes audible) under different operating conditions.
- **Stage 3 – Compliance testing**: Full compliance testing to Regulation 138 of the best ranked sounds from Stage 2.

However, due to the unavailability of any suitable existing AVAS, this programme was put on hold (a more detailed description of how that programme would have been undertaken is presented in Appendix D) and an alternative test programme undertaken as described below.

6.1 Trackside evaluation

Due to the unavailability of a compliant AVAS that was suitable for evaluation, agreement was sought for the project team to evaluate a mock-up system on a fully electric bus. The equivalent AVAS sound used for this testing was a previously recorded engine sound (from an ADL Enviro 400 bus) with no additional enhanced frequencies to aid detection.

The aim of this assessment was to evaluate the difference in detection of an electric bus with and without basic additional sound emitted from a loudspeaker mounted at the front and the rear of the bus.

6.1.1 Overview of the assessment

Participants stood blindfolded at the side of a simulated road located at the Noise Site at Millbrook Proving Ground. Four participants were located at 10 m intervals along the trackside. A speaker was located at a fixed distance behind each participant generating background noise at a sound level of 65 dB(A), which is appropriate for an urban street with a high traffic level. Figure 6-1: T shows the track layout for the testing.

The participants were passed by a test bus at one of two constant driving speeds (10 and 20 km/h). The bus was fitted with speakers for emitting the additional sounds; these were located at the front and rear of the bus, on the centre-line and at a height of 800 mm.

This was repeated three times (once per condition).

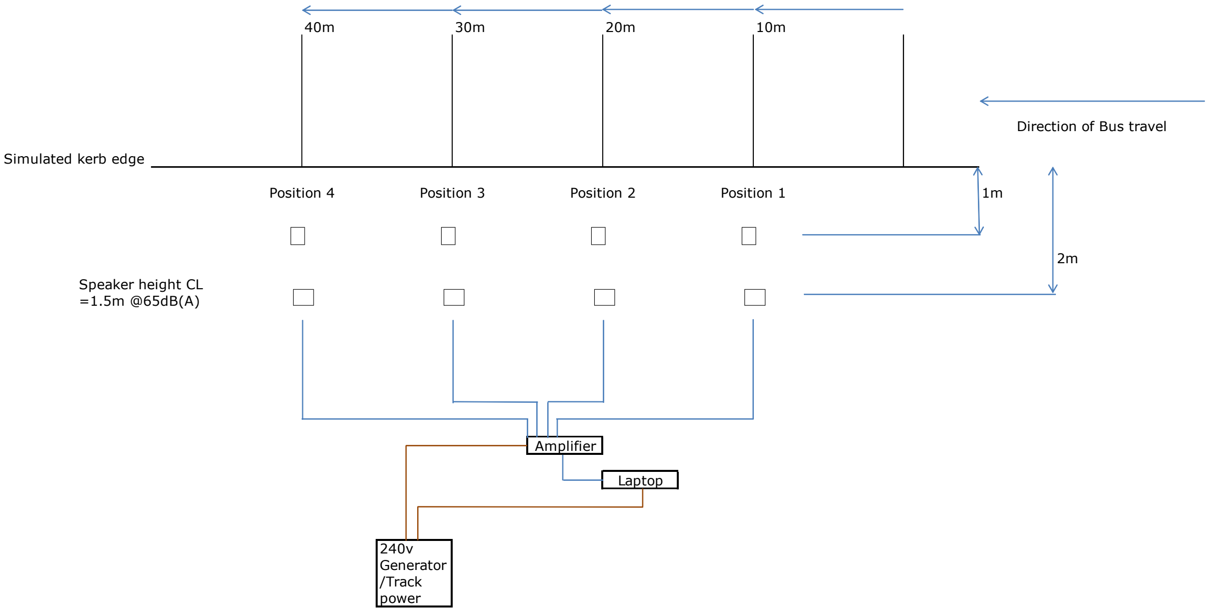


Figure 6-1: Track layout

Participants were asked to indicate when they could hear the approaching vehicle. The time interval between this indication and the time when the vehicle passed the participant's position was recorded so that time to collision (TTC) were a pedestrian to step into the path of the vehicle at the moment they heard the vehicle could be calculated.

6.1.2 Experimental design

The test used a 2 x 3 factorial within-participants design with two independent variables:

- **Vehicle speed condition** comprising two levels
  - Speed = 10 km/h.
  - Speed = 20 km/h.
- **Additional sound condition** comprising three levels:
  - No additional sound.
  - Additional sound emitted only from the rear of the test bus.
  - Additional sound emitted only from the front of the test bus.

The additional sound was a recording of the engine noise emitted by a conventional (non-hybrid) diesel bus, as previously described.

There is one dependent variable (TTC, operationalized as the time interval between the participant indicating they can hear the bus and the moment the bus passes the participant's position).

6.1.3 Participants

There were 24 participants, representative of the UK adult population (18-65) in terms of age and gender, all with normal hearing. Participants were recruited by Millbrook Proving Ground.

6.1.4 Experimental procedure

Prior to starting the experiment, participants read a Participant Information Sheet, and read and signed a Consent Form. They were then taken to the trackside.

There were four participant stations at the trackside, each equipped with:

- A loudspeaker mounted at head height behind the participant to play background sound recording; all loudspeakers were connected to the same audio player.
- A button connected to a data logger.
- An IR transmitter/receiver pair, connected to data logger.

The participant stations were spaced at 10 m intervals along the track, as shown in Figure 6-1: T. This was sufficient separation for the noise level at a given station due to the loudspeaker at that position to be unaffected by the noise emitted from loudspeakers at other stations.

Participants received a briefing at the trackside and were familiarised with the equipment. Participants were blindfolded before each bus run began.

Researchers started the background sounds playing through the loudspeakers at each participant station before the test bus began each run.

Figure 6-2: Test set up showing bus approaching participants (left), bus with rudimentary added sound on front level with participant and background noise speaker (middle), participant holding trigger switch (right)

The test bus accelerated to its target speed (10 or 20 km/h) in the run-up zone. The end of the run-up zone was sufficiently distant from the closest participant station that the electric bus (when not emitting additional sound) travelling at 20 km/h at that point could not be heard above the background noise at that station.

Each participant pressed the button at the point where they judged that they could hear the approaching bus above the background sound. The time at which the button was pressed was recorded by the datalogger.

As the bus passed each participant's position, it interrupted the IR beam at that position causing its output relay to switch. The time of this switch was recorded by the datalogger.

After passing all four participant positions, the test bus returned to its starting position.

The background sound levels at the participant positions, and the additional sound condition of the test bus, were adjusted as necessary for the next run.

Each participant experienced all three additional sound conditions in each of the background sound conditions (six conditions in all). The order of presentation of the six conditions was randomised.

6.1.5 Analysis

TTC was calculated from the time interval between the participant pressing the button and the bus interrupting the IR beam. Data was inspected and obvious outliers removed from the dataset.

TTC data was analysed using a Repeated-Measures ANOVA. Analysis of variance (ANOVA) is an inferential statistical test. It is used to compare the means of three of more treatments to determine whether the observed differences between them can be attributed to the effects of the treatment or could have occurred by chance. It calculates a test statistic, *F*, which is defined as the ratio of the variance of the group means to the mean within-groups variance:

- It compares the differences between the means of the groups to the average width of the distribution of data within each group.
- Average spread of the data within each group.

The larger the value of *F*, the larger the differences are between the groups, relative to the average spread within groups. The numbers in brackets after *F* refer to the degrees of freedom in the analysis. The probability *p* refers to the likelihood that the observed results from the sample could have occurred by chance, if in the population from which the sample was drawn there were no differences between those groups.

Conventionally, results are described as "statistically significant" if *p* is less than or equal to 0.05, meaning that the likelihood that the results could have been obtained by chance (rather than representing a real effect) is less than or equal to one in twenty."

It is the standard way to analyse within-participants experiments where each participant receives three or more treatments (i.e. experiences three or more conditions). This was the case in the acoustic conspicuity track test, where each participant experienced six conditions (3 warning sound conditions x 2 bus speeds).

The benefit of using ANOVA is that it allows us to state that the treatment caused the outcome, rather than the outcome being caused by random error (if the analysis finds significant effects). If this is not done, we have a set of means for each treatment, but don't know whether the apparent differences between them can be attributed to the effects of treatment variable or not. For instance, in the acoustic conspicuity data, the ANOVA tells us that the observed differences in measured responses (time differences) can be attributed to the effect of the added sound on the vehicle (the differences between front, back, and no sound).

6.1.6 Results of the assessment

6.1.6.1 Sound source position

This test evaluated the most effective position for the sound source on the bus (i.e. on the front or rear of the vehicle). Data was available for 31 participants. After data cleaning (excluding participants for whom there was invalid data, e.g. button not pressed or pressed early) only the 20 participants who produced a full set of six valid data points were included in the analysis.

Figure 6-3 shows the mean time differences for each condition (two vehicle speeds: 10 km/h and 20 km/h; three sound conditions: added sound at the front of the vehicle [front]; added sound at the rear of the vehicle [rear]; no added sound [none]). Time differences were larger at the lower (10 km/h) speed. Time differences were substantially greater when the warning sound was emitted from the front of the bus. At 10m km/h there was a small difference between the time differences when the warning sound was emitted from the rear of the bus and when there was no warning sound; at 20 km/h there was no difference between these conditions.

Clearly emitting the warning sound from the front of the bus was substantially more effective; indeed when it was emitted from the rear, some participants did not respond until the bus was adjacent to them.

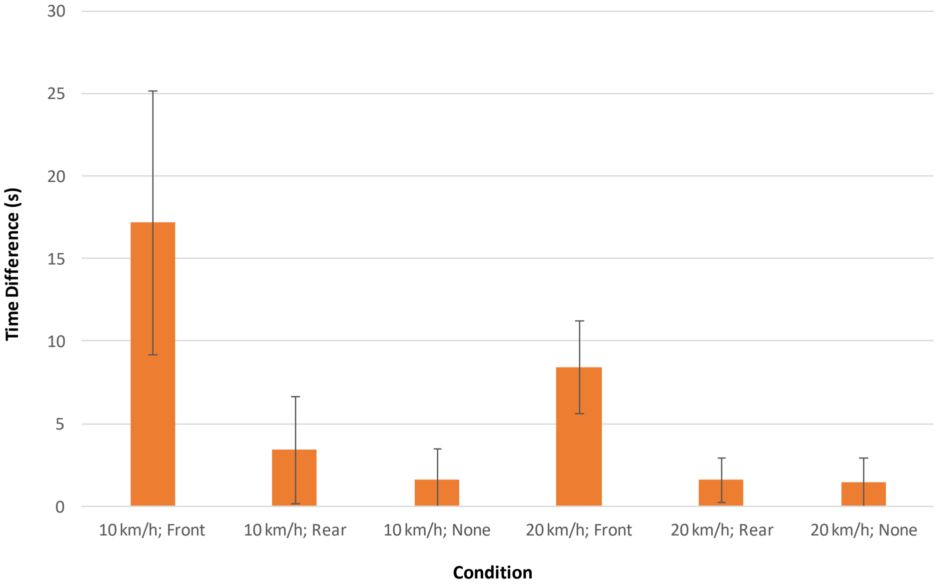


Figure 6-3: Mean time differences and standard deviation for each condition: 10 km/h and 20 km/h; warning sound front/rear/none

Formally, there were significant main effects of the vehicle speed (*F*(1,19) = 25.96, $p < 0.001$) and of the added sound (*F*(1,19) = 113.47, $p < 0.001$) on the time difference. The interaction between the vehicle speed and the added sound was also significant (*F*(1,19) = 20.05, $p < 0.001$). Post-hoc pairwise comparisons were significant for each pair of warning sounds, as shown in Table 6-1.

Table 6-1: Results of post-hoc pairwise comparisons

Comparison (loudspeaker position)	Mean pairwise difference (s)	p	95% Confidence Interval	
			Lower bound	Upper bound
Front vs Rear	10.29	< 0.001	8.12	12.35
Front vs None	11.28	< 0.001	9.02	13.06
Rear vs None	0.99	0.001	0.39	1.22

The distance at which the bus was heard is as follows:

- Vehicle speed of 10 km/h with front mounted loudspeaker: 46.46 m.
- Vehicle speed of 10 km/h with rear mounted loudspeaker: 9.31 m.
- Vehicle speed of 20km/h with front mounted loudspeaker: 46.78 m.
- Vehicle speed of 20km/h with rear mounted loudspeaker: 8.95 m.

This shows that there is a significant improvement in detection by just having a basic engine sound source mounted at the front of the bus. When the final enhanced frequencies sound is determined there should be a further improvement in detection. Therefore, any AVAS fitted to the TfL bus fleet should have front mounted speakers.

6.1.6.2 Sound source level

This tested the effect of varying the sound level emitted by the bus (at two vehicle speeds) on the time difference. There were only six participants so the statistical power of the test (its ability to discriminate differences) was low.

Figure 6-4 shows the mean time differences for each condition (vehicle speeds: 10 km/h and 20 km/h; added sound levels: 55 dB(A), 65 dB(A) and 75 dB(A)). Time differences were larger at the lower (10 km/h) speed. Time differences were greater when the warning sound level was 75 dB(A) compared to the other sound levels at both speeds. Pairwise comparisons between Sound Level 75 dB(A) and each of the other Sound Levels were significant, though the overall main effect of Sound Level was not.

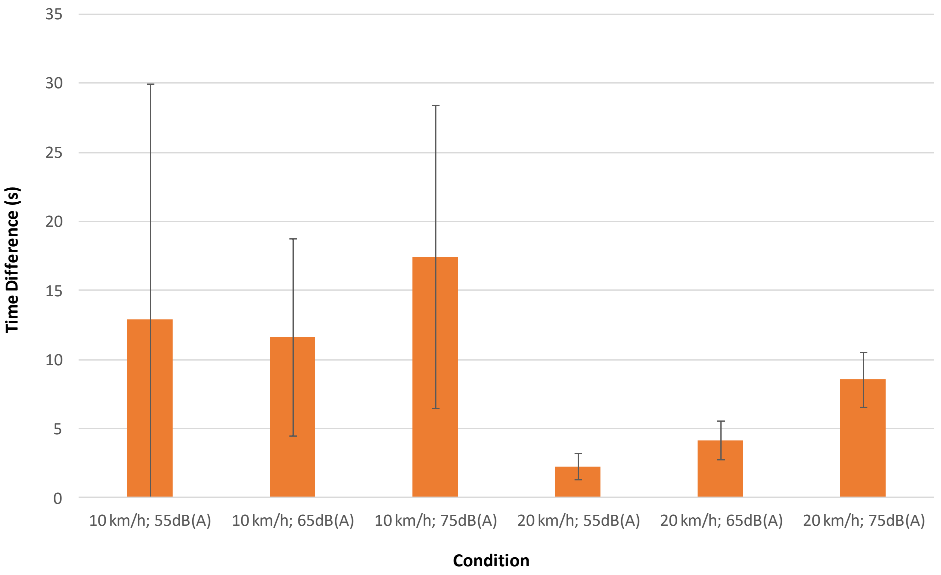


Figure 6-4: Mean time differences and standard deviation for each condition: Vehicle speeds: 10 km/h and 20 km/h; Added sound levels: 55 dB(A), 65 dB(A) and 75 dB(A)

Formally, the main effect of speed was not significant (*F*(1,5) = 5.26, *p* = 0.07); the main effect of the added sound level was not significant (*F*(1,5) = 2.99, *p* = 0.10); and the interaction between vehicle speed and the added sound level was not significant (*F*(1,5) = 0.26, *p* = 0.79).

Post-hoc pairwise comparisons were significant for the added sound Level of 75 dB(A) vs each of the other sound levels, as shown in Table 6-2. The pairwise comparison between 65 dB(A) and 55 dB(A) was not significant.

Table 6-2: Results of post-hoc pairwise comparisons

Comparison	Mean pairwise difference (s)	p	95% Confidence Interval	
			Lower bound	Upper bound
75 dB(A) vs 65 dB(A)	5.08	0.046	0.374	9.777
75 dB(A) vs 55 dB(A)	5.39	0.039	0.153	10.634
65 dB(A) vs 55 dB(A)	0.32	0.927	-8.170	8.805

This shows that the source noise level should be between 65 dB(A) and 75 dB(A). However, this test was performed with a basic engine sound source mounted at the front of the bus. The final sound with enhanced frequencies will need to be rechecked to see if the levels and detection characteristics are similar or better, as it may be possible to reduce the overall sound source level and still achieve the same performance. As a starting point, any AVAS fitted to the TfL bus fleet should have a minimum sound source level of 65 dB(A).

7 Benefit-costs analysis

A benefit-costs analysis has been undertaken to evaluate the impacts of the implementation of AVAS solutions to improve the acoustic conspicuity of buses with electric (EV) and hybrid (HEV) drivetrains. Two different categories of AVAS solution have been considered:

- **New-build AVAS solutions**: AVAS solutions fitted as part of the vehicle manufacturing process, i.e. whilst the vehicle is still on the assembly line.
- **Retrofit AVAS solutions**: AVAS solutions retrofitted onto existing vehicles that are either (a) already part of the TfL fleet or (b) have already been manufactured and are ready for sale.

7.1 Target population

Target populations were calculated for **pedestrians and cyclists**, those user groups primarily affected by the use of AVAS to improve acoustic conspicuity of quiet buses. Data was abstracted from the UK STATS19 road safety database which addresses accidents involving casualties that are attended by the police.

The selection of appropriate target populations was performed to include all fatal, serious and slight pedestrian or cyclist casualties in London (including the City of London and Heathrow Airport) between 2006-2015 involved in a collision with a EV or HEV bus, where the number of vehicles involved in the collision was no greater than two, where the STATS19 Contributory Factor 802 (Failed to look properly) was attributed by the attending police officer.

It is noted that STATS19 data does not differentiate between bus drivetrain types, so the figures are estimated based on factoring the number of relevant casualties involved in accidents with buses using a figure derived from the TfL IRIS database, namely the proportion of buses involved in collisions (in 2016/17) that had a non-ICE powertrain (this corresponded to 30.44% of buses).

The annual target populations estimated for all outcome severities relevant to the use of AVAS (fatal, serious and slight casualties) are presented in Table 7-1.

Table 7-1: Estimated average annual target populations for the use of AVAS as an acoustic conspicuity solution

Casualty type	Outcome severity		
	Fatal casualties	Serious casualties	Slight casualties
Pedestrians	2.33	17.96	58.17
Cyclists	0.10	1.69	9.84
Totals	**2.43**	**19.65**	**68.01**

7.2 Estimates of effectiveness

The estimate of the effectiveness of AVAS solutions is the reduction required in the number of pedestrian/cyclist collisions per bus-km for hybrid/electric buses to achieve the equivalent number of collisions per bus-km as for buses with ICE drive trains.

Note: This is different to the absolute effectiveness of any individual AVAS solution in reducing collisions with pedestrians/cyclists since the precise frequency content and levels of the AVAS sound and other factors such as background noise will determine the true audibility of the vehicle.

The methodology adopted followed the principles of that in the NHTSA study (NHTSA, 2016). Based on IRIS data for 2016/17 this estimated the ratio of collisions per bus-km for electric buses to collisions involving ICE buses to be 1.1477, i.e. a pedestrian/cyclist is approximately 15% more likely to have a collision with an electric bus than a conventional bus; this does not take into account the severity, cause or speed of the accident, and assumes that the only difference between the two bus types was the absence of any audible alerting cues.

Based on the above definition, an AVAS effectiveness of 15% would make the rate of collisions per bus-km the same for both electric and ICE buses. A tolerance of ±5% was assumed to derive best case and worst case scenarios. The overall effectiveness estimates for all outcome severities relevant to the use of AVAS (fatal, serious and slight casualties) are presented in Table 7-2.

Table 7-2: Estimated overall effectiveness ranges for the use of AVAS as an acoustic conspicuity solution

Casualty type	% Casualties prevented		
	Fatal casualties	Serious casualties	Slight casualties
Pedestrians	10-20%	10-20%	10-20%
Cyclists	10-20%	10-20%	10-20%

7.3 Implementation and fleet fitment timescales

Timescales for implementation of AVAS solutions are primarily driven by Regulation 138, which requires that AVAS be fitted

- on **all new bus models** (new designs requiring type approval) fitted with HEV, EV, FCV and FCHV drivetrains from July 2019, and
- on **all newly registered vehicles** with these drivetrains from September 2021.

Any earlier implementation, and particularly any retrofit implementation of AVAS on the existing TfL quiet bus fleet (which is not addressed by Regulation 138), will be determined independently by TfL policy.

Timescales were determined via discussions with bus manufacturers for both the new-build and retrofit AVAS solutions to develop a fleet fitment/penetration roadmaps for each solution. In each case, three separate development stages were identified, namely:

- **Prototyping** (development and testing of AVAS models).
- **Production of 1st AVAS model** (potential best practice preference): This covers first-to-market models and applies in that period when AVAS is not a mandatory requirement but might gain preference as part of the procurement process.
- **Production of more than 3 AVAS models** (potential mandatory fleet requirement). This represents the ability to more widely adopt AVAS throughout the TfL fleet, and assumes that three or more AVAS models will be commercially available.

Table7-3 summarises the development and fleet fitment/penetration information for new-build AVAS solutions and retrofit AVAS solutions respectively.

Table7-3: Fleet fitment and policy implementation timescales for use of retrofit and new- build AVAS solutions as an acoustic conspicuity safety measure

Safety measure solution	First to market	Date policy implemented	Full fleet adoption (years)	
			Retrofit	New-build
AVAS	2019	Jan 2019 for existing TfL fleet (TfL policy) July 2019 for new design buses (Regulation 138) September 2021 for newly registered buses (Regulation 138)	2	12

7.4 Casualty benefits

The following tables summarise the annual change in casualties expected in London during the period 2019-2031 resulting from the regulated fitment and use of AVAS as a measure to improve the acoustic conspicuity of buses with non-ICE drivetrains (i.e. those fitted with HEV, PEV, EV, FCV or FCHV drivetrains).

Table 7-4 summarises the changes for new-build AVAS solutions; Table 7-5 summarises the changes for retrofit AVAS solutions. In each case, the outcomes are then monetised to estimate the societal value of these casualty reductions.

Table 7-4: Estimated total change in number and value (NPV) of incidents over the 12-year analysis period (2019-2031) resulting from use of new-build AVAS solutions as an acoustic conspicuity safety measure

Casualty type	Number of incidents (n)			Overall value (NPV) of Incidents (£M)
	Fatal casualties	Serious casualties	Slight casualties	
Pedestrians	1.45 – 2.90	11.16 – 22.33	36.16 – 72.33	5.54 – 11.09
Cyclists	0.09 – 0.17	1.43 – 2.86	8.33 – 16.65	0.58 – 1.17
Totals	1.54 – 3.07	12.59 – 25.19	44.49 – 88.99	6.13 – 12.26

Table 7-5: Estimated total change in number and value (NPV) of incidents over the 12-year analysis period (2019-2031) resulting from the use of retrofit AVAS solutions as an acoustic conspicuity safety measure

Casualty type	Number of incidents (n)			Overall value (NPV) of Incidents (£M)
	Fatal casualties	Serious casualties	Slight casualties	
Pedestrians	7.51 – 15.02	57.81 – 115.62	187.25 – 374.50	28.80 – 57.60
Cyclists	0.33 – 0.65	5.44 - 10.89	31.68 – 63.36	2.23- 4.47
Totals	7.84 – 15.67	63.25 - 126.50	218.93 – 437.86	31.03 – 62.06

7.5 Cost implications

The costs of AVAS requirements based on its regulated introduction and use can be divided into five key cost categories based on:

1) Differences in **technology costs** (development, manufacturing and certification).
2) Difference in **implementation costs** (including installation).
3) Difference in on-going **operational costs**.
4) Differences in **insurance claims costs**.
5) Differences in **environmental and infrastructure costs**.

Estimated *current costs* for the first three categories were identified based on consultations with relevant stakeholders, as follows:

- **Technology costs**: £320 – £600 per bus for new-build AVAS solutions; £400 – £750 per bus for retrofit AVAS solutions.
- **Implementation costs**: £100 – £240 per bus (2-4 person-hours) for installation of retrofit AVAS solutions; no additional installation costs were identified for new-build AVAS solutions.
- **Operational costs**: £100 – £150 per bus per year for replacement of components/ systems due to wear and/or damage, irrespective of whether the AVAS systems is new-build or retrofit.

Table 7-6 and Table 7-7 present the estimated changes in technology, implementation and operational costs per bus and total fleet costs over the 12 year analysis period for new-build AVAS solutions and retrofit AVAS solutions respectively. The most comprehensive application of retrofit AVAS solutions considered involves fitment to all existing EV and HEV buses in the TfL fleet as well as to future purchased vehicles where AVAS is not fitted as part of the manufacturing process.

The annual change in incidents may be used to estimate the changes in annual insurance claims and premiums that may be expected by regulating the use of AVAS for the different system types (new-build and retrofit). Changes in the annual value of insurance claims are highlighted in Table 7-6 and Table 7-7 with respect to new-build AVAS solutions and retrofit AVAS solutions respectively. Average annual insurance claim and premium costs were calculated from operator-provided data, combined with the annual changes in incidents for each outcome severity.

Cost differentials resulting from environmental or infrastructure costs were not considered within the scope of this safety measure.

Table 7-6: Estimated changes in costs per bus and total fleet costs over the 12-year analysis period (2019-2031) resulting from the use of new-build AVAS solutions as an acoustic conspicuity safety measure

Cost description: New-build AVAS	Cost (NPV) per bus (£)	Total cost (NPV) (£M)
Change in technology costs	299 – 561	2.81 – 5.28
Change in implementation costs	0	0
Change in operational costs	595 – 893	5.60 – 8.40
Change in insurance claims costs	(133) – (54)	(1.25) – (0.51)
Totals	762 – 1,400	7.16 – 13.16

Table 7-7: Estimated changes in costs per bus and total fleet costs over the 12-year analysis period (2019-2031) resulting from the use of retrofit AVAS solutions as an acoustic conspicuity safety measure

Cost description: Retrofit AVAS	Cost (NPV) per bus (£)	Total cost (NPV) (£M)
Change in technology costs	378 – 708	4.10 – 7.70
Change in implementation costs	94 – 227	1.03 – 2.46
Change in operational costs	836 – 1,255	9.09 – 13.64
Change in insurance claims costs	(688) – (281)	(7.48) – (3.06)
Totals	620 – 1,908	6.75 – 20.75

7.6 Benefit-cost analysis outcomes

Table 7-8 provides estimates for the break-even costs, discounted payback period and benefit-cost ratios over a 12 year period associated with using new-build AVAS solutions as a measure to improve the acoustic conspicuity of quiet buses. Positive benefit-cost ratios are highlighted in **green**, marginal benefit-cost ratios in **orange** and poor benefit cost-ratios in **red**. Where the total fleet costs (NPV) were calculated to reduce, benefit cost ratios were classified as **RoI** to identify safety measures likely to provide operators with a return on their investment by 2031.

Table 7-8: Estimated 12-year analysis period (2019-2031) break-even costs per vehicle (NPV), discounted payback periods and benefit-cost ratios (NPV) for the new-build AVAS acoustic conspicuity safety measure

Safety measure solution	Break-Even Costs (NPV) (£)	Discounted Payback Period	Benefit-Cost (NPV) Ratio
New-build AVAS	652 – 1,304	2,024 – 2,031	**0.47 – 1.71**

Table 7-9 provides estimates for the break-even costs, discounted payback period and benefit-cost ratios over a 12 year period associated with using retrofit AVAS solutions as a measure to improve the acoustic conspicuity of quiet buses. Positive benefit-cost ratios are highlighted in **green**, marginal benefit-cost ratios in **orange** and poor benefit cost-ratios in **red**. Where the total fleet costs (NPV) were calculated to reduce, benefit cost ratios were classified as **RoI** to identify safety measures likely to provide operators with a return on their investment by 2031.

Table 7-9: Estimated 12-year analysis period (2019-2031) break-even costs per vehicle (NPV), discounted payback periods and benefit-cost ratios (NPV) for the retrofit AVAS acoustic conspicuity safety measure

Safety measure solution	Break-Even Costs (NPV) (£)	Discounted Payback Period	Benefit-Cost (NPV) Ratio
Retrofit AVAS	2,854 – 5,708	2,020 – 2,026	**1.50 – 9.20**

8 Conclusions and next steps

From the research that has been done so far, there is evidence that shows:

- The technology used in AVAS is mature enough to be used by motor manufacturers on their electric vehicles (Category M1).
- The current sounds that are being used are developed by motor manufacturers to reflect their individual brand and vehicle characteristics.
- The technology can be transferred to buses (Category M3) provided an appropriate sound is developed to characterise a unique larger vehicle.
- There is already a European Directive and a number of associated standards to control the development and use of AVAS on cars, buses and trucks. This will require that AVAS be fitted on all new EV and HEV bus models (new designs requiring type approval) from July 2019 and on all newly registered vehicles with these drivetrains from September 2021.
- Testing has shown that a front mounted AVAS could increase detection distance by approximately 5 times compared to a rear mounted diesel engine bus.
- The results of the benefits-cost analysis indicate a positive benefit-cost ratio over the 12-year period (2019 – 2031).

Next steps

- Develop unique ‘urban’ sounds for buses. It is recommended that the selected baseline sounds should have increased peak frequency content between 600-800 Hz (to improve detectability for aging pedestrians with high Hz hearing loss), increased peak frequency content between 1,600-2,400 Hz (to improve detectability for pedestrians with normal hearing) and reduced frequency content at around 1,000 Hz (to avoid noise intrusion in neighbourhood communities and provide a quiet cabin).
- Install an AVAS solution on a test vehicle.
- Evaluate and select sound as described in Appendix D.
- Install AVAS solutions on a selected part of the TfL EV/HEV bus fleet to evaluate performance on real London routes.
- Programme the fitment of new and retrofit AVAS solutions (if appropriate).

9 References

BSI (2016). *BS ISO 16254:2016. Acoustics - Measurement of sound emitted by road vehicles of category M and N at standstill and low speed operation - Engineering method*. British Standards Institution: London.

Department for Transport (2018). *Accident and casualty costs (RAS60)*. Department for Transport (DfT).

Department for Transport (2018). *WebTAG Databook v1.11*. Department for Transport (DfT): London.

Edwards A, Barrow A, O'Connell S, Krsihnamurthy V, Khatry R, Hylands N, McCarthy M, Helman S and Knight I (2017). *Analysis of bus collisions and identification of countermeasures*. TRL Project Report PPR819: Crowthorne.

Edwards et al (2017)..

European Union (2007). Directive 2007/46/EC of the European Parliament and of the Council of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles. *Official Journal of the European Union*, L 263/1, 09 October 2017.

European Union (2009). Commission Regulation (EC) No 385/2009 of 7 May 2009 replacing Annex IX to Directive 2007/46/EC of the European Parliament and of the Council establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and se. *Official Journal of the European Union*.

Hammer E, Egger S, Saurer T and Bühlmann E (2016). Traffic noise emission modelling at lower speeds. *23rd International Congress on Sound and Vibration, Athens, Greece, 10-14 July 2016.*

Hanna R (2009). *Incidence of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles*. NHTSA: Washington DC.

ISO (2015). *ISO 361-1:2015. Measurement of noise emitted by accelerating road vehicles - Engineering method - Part 1: M and N categories*. International Organisation for Standardisation: Geneva, Switzerland.

Kim DS, Emerson RW, Naghshineh K, Pliskow J and Myers K (2012). Impact of adding artificially generated alert sound to hybrid electric vehicles on their detectability by pedestrians who are blind. *Journal of rehabilitation research and development, 49*(3), 381.

Konet H, Sato M, Schiller T, Christensen A and et. al. (2011). Development of Approaching Vehicle Sound for Pedestrians (VSP) for Quiet Electric Vehicles. *SAE*

Int. J. Engines, 4(1), 1217-1224, <https://www.sae.org/publications/technical-papers/content/2011-01-0928/>. doi:https://doi.org/10.4271/2011-01-0928.

NHTSA (2016). *Minimum sound requirements for hybrid and electric vehicles*. Federal Register.

NHTSA (2018). *FMVSS 141: Minimum sound requirements for hybrid and electric vehicles*. National Highway Traffic Safety Administration: Washington DC, USA.

Oxford English Dictionary (3rd ed.). 2018, Oxford University Press, Oxford.

SAE (2015). *J2889/1_201511. Measurement of minimum noise emitted by road vehicles*. SAE International: Warrendale, PA, USA.

Transport for London (TfL) (2018). *The Mayor's Transport Strategy.*, TfL, London Available from: https://tfl.gov.uk/corporate/about-tfl/the-mayors-transport-strategy.

Transport for London (2015). *Travel in London. Report 8*. Transport for London (TfL): London.

UNECE (2016). *Regulation No. 51.03. Uniform provisions concerning the approval of motor vehicles having at least four wheels with regard to their sound emissions*. United Nations Economic Commission for Europe: Geneva, Switzerland.

UNECE (2017). *Regulation No. 138.01 Uniform provisions concerning the approval of quiet road transport vehicles with regard to their reduced audibility*. United Nations Economic Commission for Europe: Geneva, Switzerland.

Vegt E (2016). *Designing Sound for Quiet Cars* (2016-01-1839). Society for Automotive Engineers, SAE.

Vehicle Certification Agency 2018, *Bus and Coach Certification.*, viewed 16 July 2018, <http://www.dft.gov.uk/vca/vehicletype/buses-coaches.asp>.

10 Acknowledgements

TRL would like to acknowledge the support of the bus manufacturer that loaned the bus for the track testing. We are also extremely grateful to all the participants in the track testing since their input was invaluable.

Appendix A Glossary of abbreviations and acronyms

AEB	Automated emergency braking
ANOVA	Analysis of variance
AVAS	Acoustic vehicle alerting system
BSI	British Standards Institution
BSS	Bus safety standard
CoP	Conformity of production
DVA	Driver and Vehicle Agency, Northern Ireland
DVSA	Driver and Vehicle Standards Agency, Great Britain
ECOSOC	United Nations Economic and Social Council
ECWVTA	European Community Whole Vehicle Type Approval
ECSSTA	European Community Small Series Type Approval
EV	(Pure) electric vehicle – the vehicle has an electric motor, powered from batteries which are charged by plugging into the mains
FCV	Fuel cell vehicle
FCHV	Fuel cell hybrid vehicle
FMVSS	Federal Motor Vehicle Safety Standards
GRB	Working Group on Noise (subsidiary body of the World Forum for Harmonization of Vehicle Regulations (WP.29)
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ISO	International Organization for Standardization
IVA	Individual vehicle approval
LBFTS	'Looked but failed to see'
NHTSA	National Highway Traffic Safety Administration
NSSTA	National small series type approval
OEM	Original equipment manufacturer
QRTV	Informal Group on Quiet Road Transport Vehicles (part of GRB – see above)
SAE	Society of Automotive Engineers (now SAE International)
TfL	Transport for London
TTC	Time to collision
UNECE	United Nations Economic Commission for Europe)
VCA	Vehicle Certification Agency
VRU	Vulnerable road user

Appendix B Glossary of acoustic terms and symbols

A-weighting: The A-weighting filter covers the full audible range (20 Hz to 20 kHz) and the shape is similar to the response of the human ear at the lower levels.

Frequency weighting: Correlates measured sound pressure levels with the subjective human response. The human ear is frequency selective - between 500 Hz and 6 kHz our ears are very sensitive compared with lower and higher frequencies. Various weighting filters exist, however most simple noise measurements are made using the **A-weighting** filter and the results expressed in dB(A).

Decibel (dB): A relative unit of measurement widely used in acoustics, electronics and communications. The dB is a logarithmic unit used to describe a ratio between the measured level and a reference or threshold level of 0 dB.

Frequency (*f*): Sound propagates as mechanical vibration waves of pressure and displacement, in air or other substances. Frequency is the number of times that a periodic function or vibration occurs or repeats itself in a specified time, often 1 second - cycles per second. It is usually measured in Hertz (Hz). When speaking about the frequency (singular) of a sound, it means the property that most determines **pitch**.

Frequency shift: This is the change to a single or multiple frequencies by a specified amount to create another frequency resulting in the raising or lowering of the pitch of a sound.

Hertz (Hz): The unit of **frequency** or **pitch** of a sound. One hertz equals one cycle per second.

Octave band: A range of frequencies whose upper frequency limit is twice that of its lower frequency limit. For example, the 1,000 Hertz octave band contains noise energy at all frequencies from 707 to 1,414 Hertz. The centre frequencies for those octave bands in the audible range are 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz and 16 kHz.

One-third octave band: Octave bands that are sub-divided into three parts, equal to 23% of the centre frequency. These are used to give a more detailed description of the frequency content of the noise.

Pitch: The attribute of auditory sensation (perception) that orders sounds on a scale extending from low to high. Pitch depends primarily on the **frequency** of the noise source but also on the sound pressure and waveform of the noise source.

Sound pressure level (*SPL*): Uses a logarithmic scale to represent the sound pressure of a sound relative to a reference pressure, expressed in units of decibels (dB). It is typically stated in terms of the overall (or broadband) level (across all frequency bands in the audible range), the level in a particular **octave band**, the level in a particular **one-third octave band** or the level at a specific frequency.

Tone: A sound with a definite **pitch**.

Volume: When talking about sound waves, the volume is the perception of loudness from the intensity of a sound wave. The higher the intensity of a sound, the louder it is perceived in our ears, and the higher volume it has.

Appendix C Vehicle type approval

C.1 Type approval systems

Within Europe, two systems of vehicle type approval have been in existence for over 20 years. One is based around EC Directives and provides for the approval of whole vehicles, vehicle systems, and separate components. The other is based around United Nations (UN) Regulations (formerly known as UNECE Regulations) and provides for approval of vehicle systems and separate components, but not whole vehicles.

Type approval is the confirmation that production samples of a design will meet specified performance standards. The specification of the product is recorded and only that specification is approved.

Automotive EC Directives and UN Regulations require third party approval, i.e. testing, certification and production conformity assessment by an independent body. Each Member State is required to appoint an Approval Authority to issue the approvals and a Technical Service to carry out the testing to the Directives and Regulations. An approval issued by one Authority will be accepted in all the Member States.

The Vehicle Certification Agency (VCA) is the designated UK Approval Authority and a Technical Service for all type approvals to automotive EC Directives and most UN Regulations.

C.2 Bus and coach certification

Historically, national requirements for bus and coach type approval have been subject to the systems in place within each European Member State. However, Directive 2007/46/EC as amended (European Union, 2007), as amended, introduced the basis of a European wide certification scheme for this category of vehicle. The application dates can be found in Table C.1.

Table C.1: Buses and Coaches - European Community Whole Vehicle Type Approval (ECWVTA) application dates

Category	New Type optional	New Type mandatory	Existing Type mandatory
M2 and M3 - Incomplete & Complete	29th April 2009	29th April 2009	29th October 2010
M2 and M3 - Completed	29th April 2009	29th April 2010	29th October 2011
M2 and M3 - Special Purpose	29th April 2009	29th October 2012	29th October 2014

The following routes to certification are available:

- **European Community Whole Vehicle Type Approval (ECWVTA)**: EC Whole Vehicle Type Approval (ECWVTA) is based around EC Directives and provides for the approval of whole vehicles, in addition to vehicle systems and separate components. This certification is accepted throughout the EU without the need for further testing until a standard is updated or the design changes.
- **Low volume/Small Series Manufacturers**: Full EC whole vehicle type approval (ECWVTA) is not suited to all parties, particularly those manufacturing vehicles in low numbers. In recognition of this fact there are a number of other approval routes available, including the following:
    - **European Community Small Series Type Approval (ECSSTA)**: EC Small Series Type Approval) has been created for low volume car producers only, and like full ECWVTA will allow Europe wide sales but with technical and administrative requirements that are more adapted to smaller businesses.
    - **National Small Series Type Approval (NSSTA)**: This is a UK national scheme for low volume manufacturers who intend to sell only in the UK. The advantages of NSSTA are relaxed technical requirements for some subjects, a more pragmatic approach to the Conformity of Production (CoP) requirements, and reduction in administrative requirements. Like ECWVTA, once the design is approved, individual vehicles do not need to be tested.
    - **Individual Vehicle Approval (IVA)**: Individual Vehicle Approval is a UK national scheme and the most likely route for those manufacturing or importing single vehicles or very small numbers. IVA does not require CoP as it is based on inspection of each vehicle, although most bodybuilders and converters will work with manufacturers to ensure there is no warranty compromise.

      Under IVA, vehicles have to be inspected by the Driver and Vehicle Standards Agency (DVSA) in Great Britain or the Driver and Vehicle Agency (DVA) in Northern Ireland. (Vehicle Certification Agency, 2018)

Appendix D Details of proposed test programme for evaluation and selection of an AVAS sound for BSS

D.1 Stage 1: Laboratory based evaluation

Laboratory-based evaluations of different candidate sounds will be conducted to assess:

- **Attention conspicuity**: The extent to which the sound emitted by the bus stands out from ambient noise in its auditory surroundings.
- **Annoyance**: Based on a subjective rating.

Recordings of each candidate sound will be played to research participants in the presence of two levels of background noise, namely

- 55 dB(A), corresponding to an urban street with light traffic, and
- Approximately 65 dB(A), corresponding to an urban street with heavy traffic.

Recordings will be played through headphones and will each last 5 seconds. Participants will be located in a quiet room during the testing.

The tests will enable us to rate and rank the candidate sounds. Those with the highest attention conspicuity and lowest annoyance will be preferred.

Participants will be recruited to give a representative sample of U.K. pedestrians based as far as possible on current accident data (age groups over 25 to over 75). The sample will be approximately half female, half male and a total of 40 participants will be tested.

The test design involves 40 conditions, i.e. 2 background sound levels x 20 candidate noises, each with two dependent measures (attention conspicuity and annoyance level). To control for order effects (e.g. participant fatigue, and learning) the order of presentation of conditions will be counterbalanced or randomised across the participants.

Conspicuity will be measured in one of a number of ways, to be defined in piloting. One possibility is to have participants indicate (either "yes" or "no") whether they can distinguish the sound from the background. The measure of conspicuity in this method will be the percentage of “yes” responses. Another possibility is that we try to understand how much the sound ‘grabs attention’ even when people are not searching for it. Instructions based on detecting change in the scene may be used for this, although the precise method and instructions will depend on the nature of the sound stimuli.

Annoyance will be measured by asking participants to give a subjective rating using a 7-point scale with verbal anchors (e.g. 1 = not at all annoying; 7 = extremely annoying).

D.2 Trackside evaluation

The five best scoring sounds from the laboratory-based evaluation will be evaluated in a trackside test to confirm attention conspicuity under controlled but realistic conditions.

28 participants will stand blindfolded at the side of a simulated road on a suitable test track. Several participants will be located at 10-20 m intervals along the trackside (in batches of four). They will be passed by a test bus at one of two constant driving speeds (10 and 20 km/h). This will be repeated five times (once per sound) with an electric test bus, once with the electric bus with no added sounds, and once with a conventional diesel bus of the same type (with no added sounds). The latter two conditions will serve as controls. A speaker emitting the test sounds will be located on the front of the bus. A speaker will also be located at a fixed distance behind each participant generating background noise appropriate for an urban street with a high traffic level, at a sound level of 65 dB(A).

Participants will be asked to indicate when they can hear the approaching vehicle. The position of the vehicle will be recorded so that distance of the vehicle from the participant can be calculated. Knowing the speed of the vehicle will also enable time to collision (TTC) were a pedestrian to step into the path of the vehicle at this distance to be calculated.

D.3 Compliance testing

The highest ranking of sounds from track testing will go on to full compliance testing to Regulation 138.

Appendix E Questions raised during the research

A few important questions were raised during a telephone-conference with Transport for London on the 12th June 2018. The telephone-conference concerned the acoustic conspicuity work of the Bus Safety Standard.

E.1.1 Construction and Use Regulations and AVAS

The question raised, was related to the use of AVAS at night and the Road Vehicles (Construction and Use) Regulations 1986 which could potentially prohibit the use of such a system. The particular section of the Regulations that is of interest is regulation 99 (*Use of audible warning instruments*), which states the following:

"*(1) Subject to the following paragraphs, no person shall sound, or cause or permit to be sounded, any horn, gong, bell or siren fitted to or carried on a vehicle which is –*

a) stationary on a road, at any time, other than at times of danger due to another moving vehicle on or near the road; or

b) in motion on a restricted road, between 23.30 hours and 07.00 hours in the following morning.

(2) The provisions of paragraph (1)(a) do not apply in respect of the sounding of a reversing alarm when the vehicle to which it is fitted is about to move backwards and its engine is running.

(3) No person shall sound, or cause or permit to be sounded, on a road any reversing alarm fitted to a vehicle –

a) unless the vehicle is a goods vehicle which has a maximum gross weight not less than 2000 kg, a bus, engineering plant, or a works truck; or

b) if the sound of the alarm is likely to be confused with a sound emitted in the operation of a pedestrian crossing established, or having effect as if established, under Part III of the 1984 Act."

Under this regulation, a bus can have a reversing alarm/sound of an undetermined level, which can be up to 114 dB(A), but should not sound the alarm between the hours of 23:30 and 07:00 the following morning. Current buses and HGVs can have a facility to disable the reversing alarm after 23:30 to 07:00 as required by use.

This part of the Construction and Use regulations was originally intended to prevent indiscriminate use of sounds (horns, gongs, bells or sirens) fitted to motor vehicles with environmental noise in mind. (Prior to the introduction of this regulation, a car horn could play a tune rather than the single chord used on today's vehicles).

This poses a question as to whether an AVAS system comes under the category of a horn, gong, bell or siren. Regulation 37 (*Audible warning instruments*) provides a definition of the terms horn, gong, bell or siren which is used in this regulation and in regulation 99 as follows:

"*a) "horn" means an instrument, not being a bell, gong or siren, capable of giving audible and sufficient warning of the approach or position of the vehicle to which it is fitted;*

> b) *references to a bell, gong or siren include references to any instrument or apparatus capable of emitting a sound similar to that emitted by a bell, gong or siren.*"

Regulation 37 also includes the definition for a reversing alarm and a two tone horn:

> "*c) "reversing alarm" means a device fitted to a motor vehicle and designed to warn persons that the vehicle is reversing or is about to reverse; and*
>
> *d) "two-tone horn" means an instrument which, when operated, automatically produces a sound which alternates at regular intervals between two fixed notes.*"

Unfortunately, the definition of 'horn', if using the exact wording in the Construction and Use Regulations could cover current AVAS equipment and prohibit the use of the system while the vehicle is in motion. However, the wording used was never intended to apply to this type of equipment.

Clause 1 of Regulation 99 states that "…*no person shall sound, or cause or permit to be sounded*…" As an AVAS is an automatically operated system, it cannot be activated by a person. It is therefore expected that AVAS equipment should fall outside of the scope of the Construction and Use Regulations.

We have made initial contact with the Department for Transport to get clarification as to the applicability and legal stand point and also to see if the Construction and Use Regulations can be changed or amended.

Furthermore, it is considered that the wording of Regulation 99 Clause (1) (as quoted on the previous page) might prohibit the use of an AVAS system where the driver has the ability to select whether the system is active.[6]

E.1.2 Updated sounds - Re certification?

The question of updating/changing the sound files that the AVAS uses and the requirements for re-certification if that situation arises were raised.

Regulation 138 has a section to deal with the modification and extension of approval of a vehicle type (section 7), such as a change of sound the AVAS uses.

The text reads:

> "*7.1 Every modification of the vehicle type shall be notified to the Type Approval Authority which approved the vehicle type. The Type Approval Authority may then either:*
>
> *7.1.1 consider that the modifications made are unlikely to have an appreciable adverse effect and that in any case the vehicle still complies with the requirements, or*
>
> *7.1.2 require a further test report from the Technical Service responsible for conducting the tests.*

---

[6] This option is only allowed on vehicles fitted with AVAS prior to October 2017.

7.2 *Confirmation or refusal of approval, specifying the alterations shall be communicated by the procedure specified in paragraph 5.3 to the Parties to the Agreement applying this Regulation.*

7.3 *The Type Approval Authority issuing the extension of approval shall assign a series number for such an extension and inform thereof the other Parties to the 1958 Agreement applying this Regulation by means of a communication form conforming to the model in Annex 1 to this Regulation.*"

After reviewing this text, it would appear that this type of modification has been addressed and providing that the manufacturer of the sound can confirm that the new sound complies with the regulation then it should be a paperwork exercise. However, the Type Approval Authority may want to test the vehicle to ensure compliance themselves. (This would be a test at an approved vehicle testing site such as Millbrook).

E.1.3 Added sound adjusted to background sound

The question was raised as to whether the AVAS can have a function where the sound level emitted by the AVAS can be adjusted proportionally to the background levels

The concept of this has been mentioned a number of times during this project. While it is technically feasible to achieve, it does need to be thought of carefully and designed in such a way as to take account of the fluctuating traffic noise and the potentially differing background noise levels along a typical bus route without causing excessive noise.

- Regulation 138 stipulates the minimum sound levels in each 1/3 octave band from 160 Hz to 5,000 Hz (16 bands) with an overall sound level of 50 dB(A) at 10 km/h and 56 dB(A) at 20 km/h.
- Regulation 138 also stipulates a maximum overall sound level of 75 dB(A).

Therefore, any adjustment of the sound level can be between 56 dB(A) and 75dB(A); this is a considerable difference in sound level.

Background levels on London bus routes during the day can be as high as 71-81dB(A). Under these conditions the AVAS would try to achieve the maximum sound level possible but only up to speeds of 20 km/h when the AVAS switches off. Levels at night can still be in the region of 50-60 dB(A).

During the testing at Millbrook (see Section 6.1), we evaluated the difference in sound source level and detection of the vehicle. The results showed a reduction in detection times for a source level of 65 dB(A); when the sound source was further reduced to 55dB(A) the results were non-statistical and showed that audibility could not be maintained. Therefore, there is no benefit in reducing the sound source below 65 dB(A).

Further work would need to be done to evaluate the annoyance of a fluctuating sound source of 10 dB(A), as this would depend on the actual sound used and the rate at which the AVAS would update the level.

Appendix F General cost-benefit analysis approach

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

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

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

(Equation 1)

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

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

(Equation 2)

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

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

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

(Equation 3)

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

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

Claims costs reductions for each year of the analysis period were calculated by combining average insurance claim costs (calculated from operator provided data), with the expected annual changes in incidents for each outcome severity (Equation

4). For the purposes of this report, claims reductions for fatalities was assigned a range of £35,000-45,000, seriously injured casualties assigned a range of £60,000-70,000, slightly injured casualties assigned a range of £6,000-8,000, major damage-only collisions assigned a range of £4,000-5,000 and minor damage-only collisions assigned a range of £1,000-2,000.

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

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

(Equation 4)

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

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

(Equation 5)

Benefit-cost ratios (BCR) describe the ratio of expected benefits to society (arising from the prevented casualties) to the expected costs (arising from fitment to vehicles) (Equation 6). This was calculated by taking the ratio of the net present value of the total casualty benefits to the net present value of the total costs. As ranges of estimated benefits and costs have been calculated, the greatest possible benefit-cost ratio range was estimated by comparing maximum costs against minimum benefits, and vice versa. Benefit-cost ratios greater than one indicate that the value of the benefits would exceed the costs and so the measure may be cost-effective, with higher benefit-cost ratios indicating higher cost-effectiveness. Should the total costs of implementing the safety measure solution reduce, then the benefit-cost ratio will be shown as a ‘Return on Investment’ (RoI) to indicate that the solution is likely to provide operators with a return on their investment within the analysis period.

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

(Equation 6)

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

The Transport for London (TfL) Bus Safety Standard: Acoustic Conspicuity

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

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

An Acoustic Vehicle Alerting System (AVAS) is a system to make quiet running (e.g. electric, hybrid-electric, and hydrogen) buses as identifiable to pedestrians, and other road users outside the vehicle, as a standard diesel bus. This is intended to help Vulnerable Road Users (VRUs) detect the presence of a bus and the collision risk it represents if they were to cross in front of it.

Regulation will require that electric and hybrid buses are fitted with AVAS on new models from July 2019, and on all new builds from 2021. TfL is mirroring the regulatory requirements but has chosen to implement them sooner, subject to legal review.

The current sounds that are being used are developed by motor manufacturers to reflect their individual brand and vehicle characteristics. The technology can be transferred to buses (Category M3) provided an appropriate sound is developed to characterise a unique larger vehicle. TfL is investigating the development of an "urban bus" sound. The aim of this is to harmonise the AVAS sounds across London's bus fleet, regardless of which company has manufactured the bus, thereby minimising the number of new sounds introduced into an already very busy and noisy environment, and avoid the risk of confusing VRUs.

Other titles from this subject area

PPR872	Bus Safety Standard: Executive Summary. TfL & TRL. 2018
PPR819	Analysis of bus collisions and identification of countermeasures. Edwards et al. 2018

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

ISSN 2514-9652

ISBN 978-1-913246-62-4

PPR991