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The Transport for London Bus Safety Standard: Slip Protection

Evaluation of Safety Measure

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Version	Date	Description	Editor	Technical Reviewer
1.1	30/07/2022	Corrections to Table 2-1 Added reference to TfL for latest specification in the executive summary and recommendations	AE	PSM & DH

Executive Summary

Bus Safety Standard (BSS)

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

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

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

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

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

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

This research was completed in 2018. The detailed specification, assessment procedures and guidance notes have been incorporated into the Transport for London specification for buses, which is a continuously updated document to keep pace with the latest technological and research developments. This report is not the specification for a bus and should not be used as such. Bus operators, manufacturers, and their supply chain should consult with TfL for the specification.

Slip Protection

Slips on buses are also a cause of injury for bus passengers. Numerous measurement techniques and characterisation standards are available globally to help assess the performance of bus flooring in protecting against slips. In the UK the Portable Slip Resistance Tester (PSRT) is recognised by the Health and Safety Executive (HSE) as the most appropriate device for the characterisation of the slip potential of pedestrian flooring materials. The test method involves using the PSRT pendulum device with a swinging shoe plate; the greater the resistance, the less the shoe plate moves after it hits the floor.

Three bus types were assessed using the PSRT on an existing in service bus, in different areas of the bus flooring incuding the entrance and aisle, lower and upper decks. Some small modifications to the standard measuring procedure were made in order to adapt to measuring onboard buses. This full scale assessment of bus flooring materials exercise demonstrated that the derived technique is capable of characterising the skid resistance performance of a variety of bus flooring materials in situ. Laboratory testing demonstrated that the skid resistance characterisation of these materials is also possible under laboratory conditions.

The full scale and laboratory assessment of bus flooring materials has shown that some flooring materials require a wearing-in process before they are able to achieve their full slip resistant capabilities. In consultation with material manufacturers it has become apparent that it is unlikely that some materials will be able to meet a PTV when new of greater than 36. However, given that this is the threshold for low slip risk as presented by the UK Slip Resistance Group (UKSRG) it has been deemed prudent that this level should represent a minimum requirement for bus floorings. It should therefore be specified that all materials should meet a requirement of 36 PTV from the point of entering service.

In consultation with material suppliers it is also evident that the slip resistance of flooring can change during use. This is based on factors such as measurement variability, initial wearing in period, maintenance and user perception, and other considerations raised by the manufacturers. With all of these factors in mind, it is considered appropriate that after 100,000 passengers have accessed the vehicle, or after an in-service period of 6 months, whichever is sooner, the PTV of bus flooring materials should be at least 40 PTV.

It is anticipated that implementation of this specification will help to reduce slips on board buses as passengers move around the bus.

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1 Introduction to the Bus Safety Standard (BSS)

1.1 The BSS

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

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

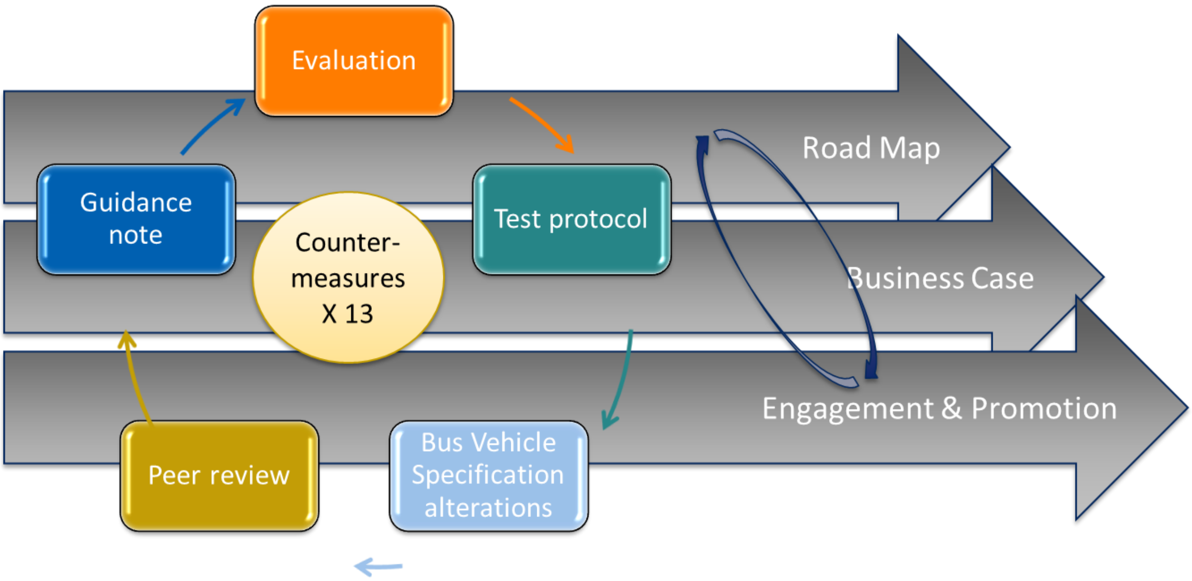

Figure 1-1: Summary of the BSS research programme

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

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

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

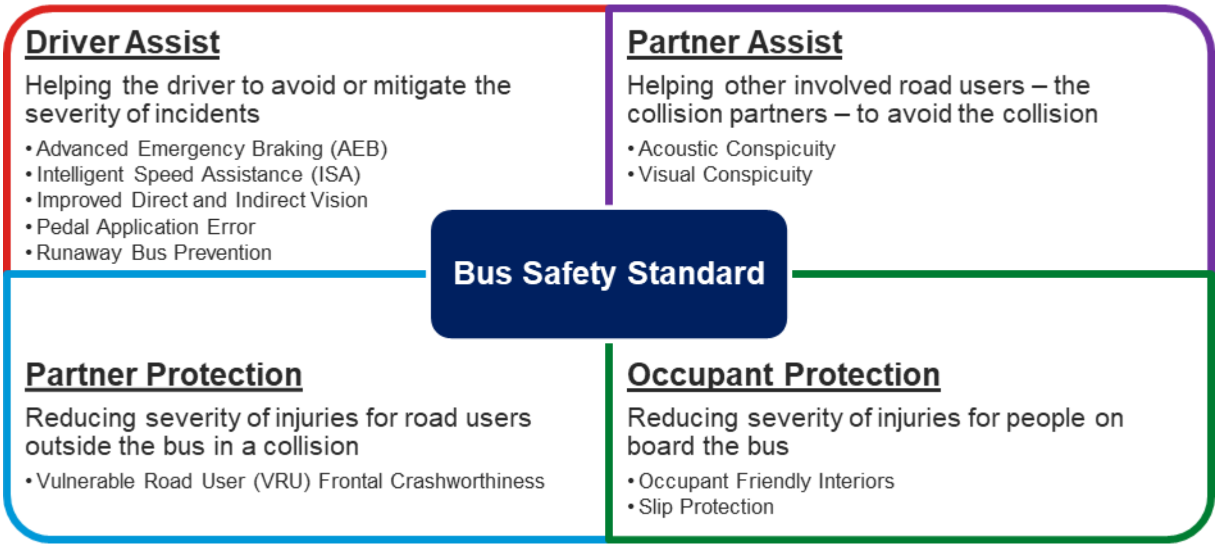

Figure 1-2: Bus Safety Measures

1.3 Slip Protection

The work reported in this document focusses on the Slip Protection (SLP) aspect of the Occupant Friendly Interiors (OCC) safety measure. The objective of the OCC safety measure is to reduce the number of passenger casualties resulting from collision and harsh manoeuvre incidents, such as emergency braking. A previous study, (Edwards, et al., 2017), recommended various safety measures based on detailed case analysis of 48 fatal files in combination with analysis of various databases of bus collisions; improving occupant interiors was one of the measures recommended. TfL further specified that the work should focus on slip protection, head restraints, grab poles and bars, and visual inspection (as an assessment tool) (Figure 1-3).

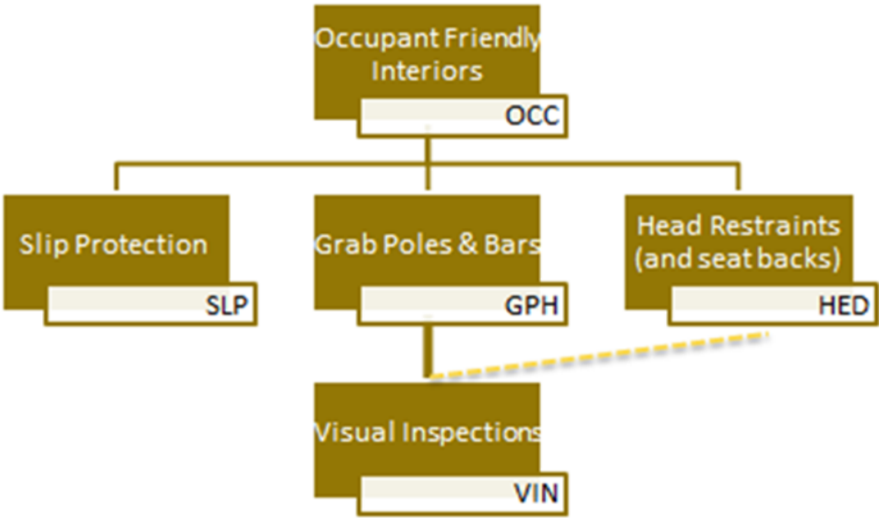

Figure 1-3: Summary of the Occupant Friendly Interiors safety measure

Slips, trips and falls in buses account for approximately half of all injuries involving buses (Transport for London, 2017). The slip resistance of the bus floor is a contributory factor to this safety issue. The aim is to provide a methodology for assessing the slip resistance of bus flooring materials, characterise the slip resistance performance of traditional bus flooring materials throughout their service life and define acceptable performance limits suitable for implementation in a standard to help mitigate slip related injuries.

One of the current safety considerations of public transport facilities, with particular reference to buses, is the occurrence of slips, trips and falls. This report discusses how slip, trip and fall injuries can be addressed by providing a general overview of the problem, how the problem relates to London buses and how it can be mitigated.

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 Table 2-1 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.

Slips onboard buses are not specifically identifiable within Stats 19. They are recorded as injuries to casualties on board the bus, but are not differentiated from injuries resulting from other mechanisms. Therefore, bus operator data was required to identify injuries resulting from slips in greater detail, which is described in sections 2.2 and 2.3.

Table 2-1: Casualty prevention value attributed to different collision types; London STATS19 data from 2006-15 (%)

Casualty Type	Collision type	Fatal	Serious	Slight	KSI	Total
Bus Passenger	Injured in non-collision incidents - standing passenger	4.2%	17.1%	23.3%	11.9%	15.2%
	Injured in non-collision incidents - seated passenger	0.5%	6.4%	13.0%	4.0%	6.6%
	Injured in non-collision incidents - boarding/alighting/other	1.6%	7.6%	5.3%	5.2%	5.2%
	Injured in collision with a car	0.5%	4.6%	10.1%	2.9%	5.0%
	Injured in collision with another vehicle	0.0%	3.1%	5.0%	1.8%	2.8%
	Total	6.9%	38.7%	56.7%	25.9%	34.8%
Pedestrian	Injured in a collision while crossing the road with a bus travelling straight ahead	30.7%	20.0%	7.0%	24.3%	19.3%
	Injured in a collision, not while crossing the road, with a bus travelling straight ahead	10.6%	7.9%	4.6%	9.0%	7.7%
	Injured in a collision with a bus turning left or right	12.2%	3.1%	1.2%	6.8%	5.2%
	Injured in other collision with a bus	2.1%	1.4%	0.7%	1.7%	1.4%
	Total	55.6%	32.5%	13.6%	41.8%	33.6%
Car Occupant	Injured when front of bus hits front of car	6.3%	1.9%	0.9%	3.7%	2.9%
	Injured when front of bus hits rear of car	1.6%	0.8%	2.8%	1.1%	1.6%
	Injured when front of bus hits side of car	1.1%	1.1%	1.8%	1.1%	1.3%
	Injured in side impact collision with a bus	2.6%	1.9%	3.9%	2.2%	2.7%
	Injured in other collision with a bus	2.1%	1.0%	1.4%	1.5%	1.4%
	Total	13.8%	6.6%	10.8%	9.5%	9.9%
Cyclist	Injured in a collision with the front of a bus travelling straight ahead	2.1%	1.2%	0.9%	1.5%	1.4%
	Injured in a collision with another part of a bus travelling straight ahead	0.0%	2.6%	1.5%	1.6%	1.6%
	Injured in a collision with the nearside of a bus which is turning	1.6%	0.8%	0.4%	1.1%	0.9%
	Injured in other collision with a bus	0.5%	3.1%	2.1%	2.1%	2.1%
	Total	4.2%	7.8%	5.0%	6.4%	6.0%

Casualty Type	Collision type	Fatal	Serious	Slight	KSI	Total
Powered Two Wheeler (PTW)	Injured in a collision with a bus travelling straight ahead	2.6%	1.3%	0.7%	1.9%	1.5%
	Injured in a collision with a bus turning left or right	0.5%	1.0%	0.7%	0.8%	0.8%
	Injured in other collision with a bus	0.5%	1.0%	0.9%	0.8%	0.8%
	Total	3.7%	3.4%	2.3%	3.5%	3.2%
Bus Driver	Injured in collision with a car	0.0%	1.5%	2.5%	0.9%	1.4%
	Injured in non-collision incidents	0.0%	0.5%	0.5%	0.3%	0.4%
	Injured in collision with another vehicle	0.5%	1.2%	1.5%	1.0%	1.1%
	Total	0.5%	3.2%	4.5%	2.1%	2.8%
Other	**Total**	**15.3%**	**7.9%**	**7.1%**	**10.9%**	**9.8%**
Casualties Total		**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

2.2 Overview of Slips, Trips and Falls

In the UK, slips and trips are the most common cause of injury at work causing approximately over a third of all major injuries and over 40 % of all reported injuries to members of the public (Health and Safety Executive, 2012). It is estimated by the UK Health and Safety Executive (HSE) that most of these incidents are slips occurring as a result of contaminated (water, talc, grease etc.) surfaces.

Falling usually occurs when the friction between the shoe sole and floor is inadequate (Chen, Chen, Chang, & Lin, 2015). The coefficient of friction (COF) is the most used parameter to quantify and express the extent of friction between a shoe sole and the floor. The higher the COF, the greater the extent of anti-slipperiness (Chang, Kim, Manning, & Bunterngchit, 2001) and friction is used as a key indicator of floor slipperiness (Chang, Matz, Grönqvist, & Hirvonen, 2010). The floor roughness, floor materials, level of contamination and the sole design of shoes are all factors effecting the measurement of COF (Chang, W.R, 2002) (Chang, W.R; Matz, S, 2001) (Liu, Li, Chen, & Chen, 2010).

The presence of water or other contaminants can substantially reduce the COF between floor and shoe. The effect of shoes treading on a surface contaminated with a liquid can be explained using the squeeze-film effect. Slips, trips and falls happen in accordance with the squeeze film formula (Equation 2-1).

$$t = \frac{K\mu A^2}{F_n}\left(\frac{1}{h^2} - \frac{1}{h_0}\right)$$

Where:

- t is the time needed to reduce the liquid thickness from initial h_0 to h
- F_N is the normal force
- K is a shape constant
- μ is the liquid viscosity
- A is the contact area between the surface

Equation 2-1 The squeeze film effect (Moore, 1972) and (Chen, Chen, Chang, & Lin, 2015)

Equation 2-1 shows that when the floor is contaminated with liquid, the higher the liquid viscosity, the longer the time required for shoes to contact the floor material and hence the higher the risk of falling (Chen, Chen, Chang, & Lin, 2015). The hydrodynamic squeeze-film theory (Proctor & Coleman, 1988) shows that to increase friction, an amount of surface texture is required. Another study (Chang, Matz, Grönqvist, & Hirvonen, 2010) also showed that for a surface smeared by liquid, the presence of a rough surface can aid in improving the squeeze-film effect. Consistent with previous studies (Lemon & Griffiths, 1997) it is revealed that fluids with higher viscosity required higher extents of surface roughness to give comparable measures of slip resistance as the thickness of the squeeze-film created between the tread and floor increased.

A study (Chen, Chen, Chang, & Lin, 2015) investigating the influences of liquid viscosity and floor roughness on floor slip resistance found that shoe materials, floor roughness and liquid viscosity had a notable impact on slip resistance. The most significant factors affecting the coefficient of friction (COF) were the shoe materials, followed by liquid viscosities and thirdly floor roughness.

2.3 Bus safety performance in London

Even though the number, and rate of bus casualties and fatalities is lower than that for other road vehicles there is still a risk to injury that could be effectively mitigated. A report on passenger casualties in non-collision incidents on buses and coaches in Great Britain stated that the majority of killed and seriously injured bus passenger casualties (64.3%) occur when the vehicle is not involved in a collision (Kirk, Grant, & Bird, 2003).

This safety measure directly targets slipping injuries by mitigating the risk of a slip event occurring. In the most recent report available, the bus safety performance indicators used for London buses showed that almost half of all injuries arising from incidents involving buses arose from slips, trips and falls on the bus (Transport for London, 2017). Moreover, the figures presented in that document showed an increase in the number of injuries arising from slips, trips and falls on buses between 2015 – 2016 and 2016 – 2017, however it is not known if this is a function of an increase in the use of buses. This information is presented graphically in Figure 2-1.

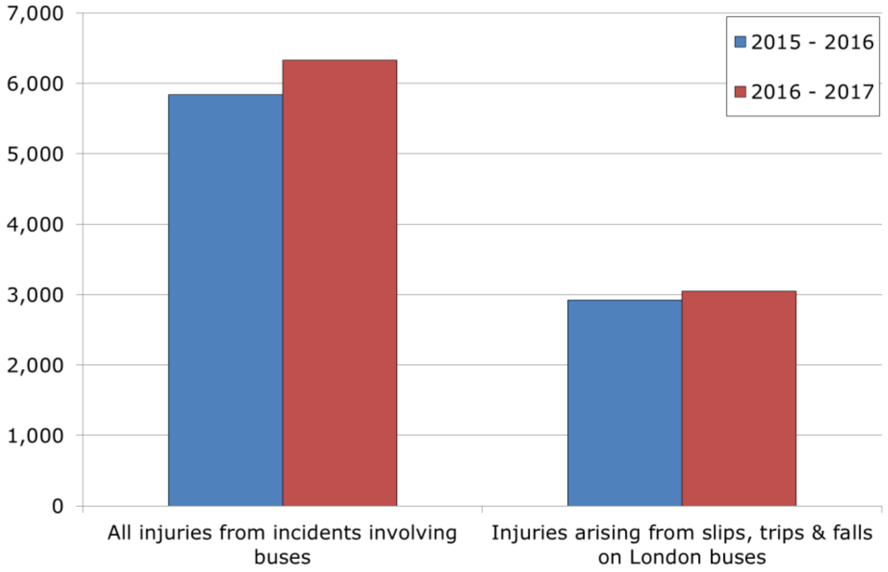

Figure 2-1: London bus injuries (produced from figures in (Transport for London, 2017))

To assess the proportion of the 2016 - 2017 figures shown in Figure 2-1 that are related to slips, the IRIS database1 was queried. Data from a three year period from April 2014 to March 2017 was used. The following filters were used to identify slips in the 'immediate cause' field due to a:

- slippery surface
- uneven surface
- poor/ slippery/ uneven surface

This revealed 97 incidents in total from the slips, trips and falls incidents table. This represents about 0.7% of the total number of incidents indicating the small size of the 'slip' problem. If the 'uneven surface' cause was discounted (because it mostly refers to the surface of the road/pavement outside of the bus) then this leaves 80 incidents. A further 8 cases were disregarded because the description reveals the slip was on the ground surface, and another 3 cases were not clear whether the bus or the ground surface was the problem.

This resulted in 69 cases where the description field of the incident was read through, and all mention a slip. 54% of the cases were due to a wet surface, mostly as a result of rain. The remaining 46% of cases did not specify a wet surface so it assumed that in these cases the floor was dry. From the 69 slip cases there were 27 where the location of the passenger within the bus was known, and 44% were by the doors (56% elsewhere). Similarly, for just the 37 slips on a wet surface there were 15 where the bus passenger location was known, and 53% were by the doors (47% elsewhere). It makes sense that the proportion is slightly higher for wet slips by the doors, because it would be expected that the majority of water would be near the doors as it would be transferred from outside by passengers getting on the bus. However, there was not a substantial difference, which perhaps indicates that water pooling and puddling near the doors is not much of a problem. None of the incidents mention a water pool or puddle on the floor, only 'wet' or 'rain'. However the IRIS database does not specifically ask if water was pooled or puddled on the floor.

It is worth noting that an additional filter was later applied to these returned results to identify incidents where an injury was sustained as a result of a slip trip or fall. Of the 37 incidents identified, 19 resulted in an injury. Given that this is almost 50% of the total number of incidents, this could suggest that the risk of serious injury resulting from slips, trips and falls on buses is low.

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[1] A database containing incident data provided by the bus operators to Transport for London

2.4 Summary of the slips casualty problem

The definition of the problem in section 2 presented a review of literature pertaining to slips trips and falls and an accident study relating to the TfL bus fleet. The work presented in this section can be summarised as per the points below:

- Slips trips and falls usually occur when the friction between the surfacing material and shoe is inadequate.
- The presence of contaminants can greatly affect the amount of friction, and by extension the slip risk through the squeeze film effect.
- The number of casualties arising from wet slips trips and falls is reported to be quite low, 19 between 2014 and 2017.

3 Existing test procedures and standards for the characterisation of flooring slip resistance

Addressing the problem of slips trips and falls on buses requires an understanding of the slip resistance performance of the bus flooring materials. This in turn requires an understanding of appropriate techniques and equipment to characterise slip resistance performance of flooring materials. This section explores the various options available for the measurement and characterisation of slip resistance. Firstly the different measurement devices available are detailed. Secondly, the various standards that use these devices are presented.

3.1 Slip resistance measurement devices

Examining the occurrence of slips, trips and falls is often initiated with the evaluation of the slipperiness of the surface involved. Terminologies that relate to slipperiness include friction and coefficient of friction (COF) and these are defined as follows (Lin, Chiou, & Cohen, 1995).

Friction is defined by the National Bureau of Standards as the force that resists the relative movement of two surfaces in contact with each other. The two surfaces can be described using the shoe sole or material of the heel and the floor material. The main types of frictional forces are static friction and dynamic friction. *Static friction* is the resisting force at the moment relative motion begins between the sole and the floor and *Dynamic friction* is the resisting force when movement is occurring without interruption.

Coefficient of friction (COF) is the horizontal force required to move the sole material over the floor material divided by the total force pressing the two surfaces together. COF is normally used to express the degree of traction between the sole and floor material. COF as a measure of slipperiness is notable only if the reading is obtained from measuring a reliable combination of sole and floor material under the appropriate environment (e.g., soapy, wet, greasy etc.).

Various devices have been developed by individuals, organisations or Federal agencies to quantify slip-resistance (the COF). The majority of these devices can be grouped as, drag/towed-sled, articulated strut and pendulum, and, these are described below (Lin, Chiou, & Cohen, 1995).

3.1.1 Dragged sleds

This group of devices typically slides a weighted scale mounted with footwear sole samples across the test surface. The device is either dragged by hand or by means of a motor at a speed that can be adjusted. The COF is obtained by dividing the force required to cause the slip by the weight of the sled. Some of the devices assess only the static friction with others measure both static and dynamic friction. A summary of the most common devices is provided in Table 3-1.

Table 3-1: Summary of Dragged sled friction testers

Device	Conforms to standard (s)	Characterisations provided
BOT - 3000	ANSI B101.1 ANSI B101.3 ANSI 137.1 ASTM F2508-13	Static COF Dynamic COF Dry and wet conditions
Tortus II	AS4586-2013	Dynamic COF Dry and wet conditions
Horizontal Pull Slipmeter	ASTM F609-05	Slip Index (Static COF x 10) Dry conditions only
Dynamometer Pull Meter	ASTM C1028-07	Static COF Dynamic COF Dry and wet conditions

3.1.2 Articulated strut devices

These devices are made up of a weight affixed to a shaft articulated at an angle to the horizontal plane. At the bottom of the shaft is a base plate containing either reference material or shoe sole material. During operation an increase in the angle of articulation is created until a slip occurs between the base plate and surface. The tangent of the angle is directly correlated with the static COF between base plate and surface.

The James Machine and the NBS Brungraber Portable Slip-Resistance Testers are the most common of this device type. In the USA, the James Machine remains the preferred industry method for assessing manufactured floor surfaces and finishes and is quoted in ASTM D2047-04 (ASTM International, 2011).

3.1.3 The ramp test

The ramp test (DIN 51097 and DIN 51130) was developed by the German standards body Deutsches Institut für Normung (DIN) and is primarily designed to assess surfaces used in work places. The methodology for this test requires a specimen of surface material to be installed on a ramp device whereby the angle of inclination can be augmented. An operator either wearing shoes with a rubber sole of Shore A hardness 96, or barefoot, stands on the surface as its angle is progressively increased. The maximum inclination achieved before the operator begins to slip characterises the slip potential of the surfacing.

The test results from shod tests are used to classify the slip potential as “R values” and tests conducted with bare feet are used to classify a “Quality group”; see Table 3-2. The test is used to characterise the static coefficient of friction and is widely used in measuring slip resistance of workplace surfaces. This test methodology is primarily used as a type approval test rather than an in-situ assessment owing to the size of the equipment required for the methodology.

Table 3-2: Ramp test classifications (German National Standards, 1992) and (German National Standards, 2004)

Slip Angle (degrees)	Barefoot classification	Shod classification
6-9	N/A	R-9
10-11		R-10
12-17	A	
18-19	B	
20-23		R-11
24-27	C	
28-35		R-12
35+		R-13

3.1.4 Roller coasters

The roller coaster method utilises a slider mounted on a coasting trolley that moves over a surface with a standard initial velocity. The reaction force between the slider and surface slows the trolley and the distance travelled by the vehicle is inversely proportional to the surface's slip resistance. The primary device identified in the literature is the SlipAlert.

This device provides an estimation of the slip risk associated with the surfaces by using the conversion table shown in Table 3-3:

Table 3-3: Slip alert result characterisations

Classification	Counter reading
High risk of slip	<130
Medium risk of slip	130-173
Low risk of slip	>173

3.1.5 Pendulum testers

Pendulum type devices use a rubber slider as an analogue for shoe sole material, or barefoot contact. A slider of hardness 96 IHRD is used to determine slip by shod pedestrians and a slider of hardness 55 IHRD for barefoot pedestrians. The appropriate slider is installed on to a weighted foot that is in turn mounted on a swinging arm. During a test the arm is brought up so that it is horizontal with the surface to be tested and released. The rubber foot is then swept over on the floor surface at a reasonably high speed and for a set distance. The loss in energy of the pendulum at the start and end of the swing quantifies the dynamic friction.

The most common device of this type is the Portable Slip Resistance Tester (PSRT) (Figure 3-1) which is governed by British standards BS 7976-2 (British Standards Institution, 2002) and BS EN 13036-4 (British Standards Institution, 2011).

Figure 3-1: The Portable Skid Resistance Tester

Results from the PSRT (expressed as Pendulum Test Value (PTV)) can be used to classify surfaces as having High, Moderate or Low Slip Potential. The threshold of the values can be shown in Table 3-4:

Table 3-4: Pendulum test classifications (UK Slip Resistance Group, 2016)

Classification	Pendulum Test Value
High slip potential	0-24
Moderate slip potential	25-35
Low slip potential	36+

The PSRT is the preferred device of the HSE for the characterisation of slip potential. Furthermore the devices are readily available for purchase in the UK and require little training to use; alternatively, numerous test houses are able to supply PSRT services.

3.2 Existing standards for the assessment of slip resistance

This section presents a review of international standards pertaining to the characterisation of slip resistance.

3.2.1 Australia

The four main guides relating to pedestrian slip resistant surfaces in Australia are presented below.

HB 197:1999 An Introductory Guide to the Slip Resistance of Pedestrian Surfaces (Standards Australia, 1999).

HB 198:2014 Guide to the Specification and Testing of Slip Resistance of Pedestrian Surfaces (Standards Australia, 2014) gives advice on suitable slip resistance levels of flooring materials in some typical applications. The benchmark for certifying compliance with slip resistance specifications and the design for slip resistance of sloping surfaces are also presented.

AS 4586:2013 Slip resistance classification of new pedestrian surface materials. (Standards Australia, 2013) provides details on four test methods for the slip resistance characterisation of new surfaces receiving pedestrian traffic.

Similarly, AS 4663:2013 Slip resistance measurement of existing pedestrian surfaces. (Standards Australia, 2013) presents the same four methods (as AS 4586) for categorising the slip resistance of existing pedestrian surfaces:

- PSRT testing under wet conditions
- PSRT testing under dry conditions
- Ramp testing under wet barefoot conditions
- Ramp testing under oil-wet shod conditions

3.2.2 United States of America

The American Society for Testing and Materials (ASTM) provides two standard methodologies for the characterisation of flooring slip resistance. These methodologies are presented below and utilise the PSRT and James Machine.

ASTM E303-93 (2013) Standard Test method for Measuring Surface Frictional Properties Using the British Pendulum Tester. (ASTM International, 2013). This methodology specifies the use of the PSRT. The method may be used to determine the relative effects of various polishing processes or materials or material combinations. The test method does not take responsibility for risks arising from falls, slips and trips and is noted in Section 1.5 of the Scope of the Standard which states that “This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.”

ASTM D2047-2011 Standard Test Method for Static Coefficient of Friction of Polish-Coated Flooring Surfaces as Measured by the James Machine (ASTM International, 2011). This standard presents a laboratory test method covering the use of the James machine for evaluating the static coefficient of friction of polish-coated flooring surfaces regarding human mobility safety. The test also provides a conformity benchmark to meet the requirement for a non-hazardous polished walkway surface. The test method is however not aimed for use on ‘wet’ surfaces or on surfaces where the texture, projections, profile or clearance between the sculptured patterns of the surface does not permit adequate contact between the machine foot and the test surface. This test method also does not take any responsibility for risks arising from slips, trips and falls and states in Section 1.4 of the scope of the standard that ‘*This* *standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use*.'

3.2.3 Germany

In Germany two main methods are used for testing floor coverings; both are variations on the ramp test and are standardised in the following two documents.

DIN 51097: 1992 Testing of floor coverings, determination of the anti-slip properties, wet-loaded barefoot areas, walking method and ramp test. (German National Standards, 1992). This standard is used to estimate the anti-slip attributes of floor coverings which are meant to be used in wet-loaded barefoot areas. The treads of steps and ladders are also included under floor coverings. It uses barefoot operators with soap solution as the contaminant for testing.

DIN 51130: 2004 Testing of floor coverings, determination of the anti-slip properties, workrooms and fields of activities with slip danger, walking method and ramp test. (German National Standards, 2004). This standard is similar to that described above but, uses heavily cleated EN ISO 20345 safety boots with motor oil contamination for testing.

The classification of the slipperiness of products for sale by most European flooring manufacturers is done by means of the ramp-type test. The HSE has however expressed reservations about these test methods stating that neither test method makes use of contaminants that are representative of those commonly used in workplaces. In addition, the manner in which the results are expressed and applied is a matter of concern as there are different classification types specified and the slip angle ranges overlap in the two methods, see Table 3-2. These ambiguities have led to incorrect floor surfaces being installed (Health and Safety Executive, 2012).

3.2.4 Great Britain

Four standards were identified from the British Standards Institution (BSI) and one set of guidelines from the UK Slip Resistance Group (UKSRG).

BS EN 13036-4:2011, BS 7976 – 1:2002, BS 7976 – 2:2002 and BS 7976 – 3:2002 are descriptive standards and define the specification, operation, and calibration of the PSRT. No guidelines are provided in these standards regarding the characterisation of slip risk.

The UK Slip Resistance Group Guidelines, The Assessment of Floor Slip Resistance. 2016. Issue 5 (UK Slip Resistance Group, 2016) provide more knowledge into pedestrian slipping. These guidelines encourage the use of slip resistance test methods that have been demonstrated to precisely and definitively show the slip likelihood of floor materials. The UKSRG provides guidelines detailing the recommended method for assessing the slip resistance of walkways and flooring materials. The evaluation method is tailored to laboratory measurements and measurements in on-site conditions and is not restricted to the evaluation of internal surfaces.

The UKSRG and the HSE (Health and Safety Executive, 2006) endorse the use of the PSRT and an appropriate roughness meter (including non-contact types) as the two instruments for assessing slip resistance. There are two main reasons for the PSRT being selected by the UKSRG and the HSE. Firstly, it replicates the same hydrodynamic uplift attributes arising when a person slips in liquid-contaminated conditions. Secondly, good association between the readings provided by the instrument and the occurrence of pedestrian slipping incidents has been noted since the 1940s (UK Slip Resistance Group, 2016).

3.3 Summary of slip resistance standards

Section 3.2 presented a summary of measurement devices and standards used for the measurement and characterisation of flooring slip resistance. From the literature review the following summary points prevail:

- Numerous measurement techniques and characterisation standards are available globally.
- In the UK the PRST is recognised by the HSE as the most appropriate device for the characterisation of the slip potential of pedestrian flooring materials.
- In the UK the characterisation of slip potential is standardised in the UKSRG guidelines (The UK Slip Resistance Group, 2016).

4 Bus flooring materials

A number of bus flooring materials available in the United Kingdom (UK) and United States of America (USA) have been identified and are discussed in this section. Text pertaining to the characteristics and performance of the products has been extracted from company sales literature and has been amended to protect the anonymity of the products.

4.1 Company A

Company A provides descriptions for three main bus flooring products namely Product 1A, Product 2A and Product 3A.

Product 1A is designed to give robust performance in vehicles exposed to the daily thumping of urban commuters. It is made up of highly resilient vinyl flooring provided in three thicknesses (1.8mm, 2.2mm, 2.7mm). It has no phthalates, contains bio-plasticiser and aluminium oxide grains for enhanced slip resistance.

Product 2A is produced in three thicknesses (1.8mm, 2.2mm, 2.7mm) making it a highly tough, functional flooring meeting all installation and compliance requirements. Its creation comprises the use of silicon carbide and aluminium oxide grains for slip resistance and its dimensional stability is strengthened by incorporating Polyvinylchloride (PVC). The product gains from a technology for better cleanliness, minimised dirt pick up and strengthened colour retention.

Product 1A and Product 2A are safety flooring to EN 13845 and ASTM F1303. The slip resistance properties of Product 1A and Product 2A are given as:

• BAM[2]	Dry - very slip resistant Wet – slip resistant
• TRRL[3]	≥ 36
• ASTM	≥ 0.6

Product 3A is marketed as a wood surfacing with a PUR (Polyurethane) coating to protect against scuffs and stains. The slip resistance properties of this product are claimed to match that of the other products from this company. Images from the company's website show that this product has been installed on airport transit and a bus route outside of London.

4.2 Company B

Company B provides floor coverings made of PVC (Polyvinyl Chloride) for use in vans, buses and other vehicles.

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[2] Reference to a "BAM" rating could not be identified in any of the literature reviewed and so the characterisation of the material in this way is questionable.

[3] The term TRRL or TRL is often used as a synonym for pendulum test results and values with these terms were collected using the methodology outlined in section 3.2.4.

Product 1B flooring comprises the incorporation of corundum (extremely hard crystallised alumina, used as an abrasive). This flooring has an anti-slip coefficient at the level of R10 (in conformity with DIN 51130) and also satisfies the specification of European Directive 95/28/EC of 24th October 1995 on burning behaviour of materials used in interior construction of certain categories of motor vehicles. The product is manufactured in a 200cm width and thickness of 2.0mm with an unwoven fabric backing material.

Product 2B flooring is produced in the width of 130cm and in two thicknesses of 1.5mm and 2.2mm. It meets the flammability specifications of ISO 3795. There is another type of Product 2B provided in the width of 130cm and thickness of 2mm*.* It is produced in a non-flammable form meeting the specifications of ISO 3795 motorisation requirement. The surface design is both anti-slip and easy to wash. Product *3B* is a variant of Product 2B but with the addition of raised dots.

4.3 Company C

Company C produces ten main types of flooring materials for buses. Its products are described as high performance floor covering for high footfall areas. Their products can be categorised in two main kinds:

- Product 1C uses a transparent wear layer with anti-slip particles laid onto a printed layer
- Product 2C uses a wearing layer embossed with anti-sliding particles

Slip resistance of the materials are to the DIN 51130 specification with the requirement for Product 1C and Product 2C being mostly R10 and a few for Product 1C being R9.

4.4 Company D

Materials made by *Company D* utilise cork and rubber to provide wear and slip resistance properties. Two main products are manufactured by *Company D* for bus floorings.

Product 1D is a synthetic rubber bonded cork material with a “high degree of resistance to oil and grease”. Product 1D is produced in thicknesses of 2.5mm to 6.5mm. The slip resistance of Product 1D has been characterised using the pendulum test and typically provides dry test values of 81 and wet values of 36 PTV.

Product 2D is a natural rubber bonded cork material made particularly for the transport industry. The slip resistance of Product 2D, as characterised using the pendulum tester, is 95 PTV in dry conditions and 32 PTV in wet conditions.

4.5 Company E

Company E provides textiles, flocked flooring and safety vinyl for buses and coaches. All products meet international industry requirements and have a slip resistance rating of up to R13. Company E products include Product 1E, Product 2E and Product 3E. Slip resistance for these products are measured to DIN 51130 (German National Standards, 2004).

Product 1E is a durable slip resistant vinyl flooring. The slip resistance is improved with carborundum or aluminium oxide particles giving an R10 to R12 rating.

Product 2E is a “special” surface comprising a high content of PVC and offers “superior, long lasting appearance and performance”. Its slip resistance has been characterised as R10.

Product 3E is a Nylon textile material that looks and feels like a carpet but with straight fibres allowing ease of cleaning. The slip resistance values specified are R13 and DS: > 0.30.

4.6 Summary of bus flooring materials

An assessment of the bus flooring materials available in the UK was carried out in section 3, this review has demonstrated that:

- Flooring materials are available meeting a PTV of 36 (the requirement for a low slip risk material as defined in the UKSRG guidelines (The UK Slip Resistance Group, 2016).
- 13 materials used for bus flooring, manufactured by 5 companies were identified.
- The materials can be grouped into the following categories:
    - Mineral Encapsulated Composite (MEC). Products, 2A, 1B, 2C and 1E.
    - Smooth Vinyl. Products, 1A, 2B and 2E.
    - Textured vinyl. Product 3B.
    - Rubber bonded cork. Products,1D and 2D.
    - Fabric. Product 3E.
    - Transparent layer with “anti-slip” particles. Products, 3A and 1C.

5 Development of a testing protocol for the BSS

PSRT testing under wet conditions is increasingly being accepted as the most useful method of slip resistance characterisation. The main advantages associated with the Wet Pendulum Test over the other test methods are given as:

- Portable and used for on-site testing
- The most likely test to be used in an investigation after a slip incident
- Wet test using water – it is the most frequently experienced contaminant
- Reliable results with minimal operator impact
- Utilised in combination with accelerated wear testing (AWT)

The UKSRG guidelines (UK Slip Resistance Group, 2016) provides the most comprehensive guidance and risk characterisation methodology of all the documents reviewed in Section 3. However, before a decision can be made regarding the suitability of the test methodology for inclusion in the BSS, it is prudent to critique the standard for its applicability to buses. The results of this critique can be used to suggest amendments to the UKSRG guidelines and to design a test protocol and safety levels appropriate for buses.

The following sub-section therefore critiques the UKSRG Guidelines and proposes a regime specifically related to buses. For simplicity, knowledge of the PSRT and the UKSRG guidelines have been assumed, and only the sections of the UKSRG guideless requiring amendment for buses have been presented. Section 6 provides the testing approach and the results of the testing are discussed in sub-section 6.5.

5.1 The use of a roughness meter to provide supplementary information

Chapter 7 of the UKSRG guidelines advocates the use of a roughness meter to characterise the microtexture of the surface in terms of Rz values. The UKSRG guidelines state that microtexture measurements should be used as supporting information in conjunction with the measurements made using the PSRT. The Guidelines also state that the benefit of making microtexture measurements is limited as per the excerpt below:

“However, the interpretation of microroughness measurements is based on comparison with slip resistance measurements, so on that basis, it cannot be considered as reliable as Pendulum Test Values.” (UK Slip Resistance Group, 2016)

The guidelines also suggest that the making of microtexture measurements is simply a tool that may be useful in the identification of areas that provide poor wet slip resistance, where direct measurements of slip resistance are not possible.

"In some situations, for example on stair treads, the edge of a stair nosing or on the curved surface of a bath or shower tray, a measurement of roughness might be the only measurement it is possible to make." (UK Slip Resistance Group, 2016)

For bus flooring, because wet slip resistance measurements are being made directly the use of the roughness meter is essentially moot. The same can also be said for other material properties that influence skid resistance measurements such as resilience and hardness.

For these reasons the direct measurement of slip resistance is considered the most appropriate method of characterising slip risk and the assessment of other physical properties that contribute to the generation of slip resistance is unnecessary.

It is recommended that the use of the roughness meter is omitted from the test methodology.

5.2 Resilience, temperature and friction

Table 1 of the UKSRG guidelines shows the change in resilience of the rubber slider (slider 96) in response to temperature. This table has been reproduced graphically in Figure 5-1.

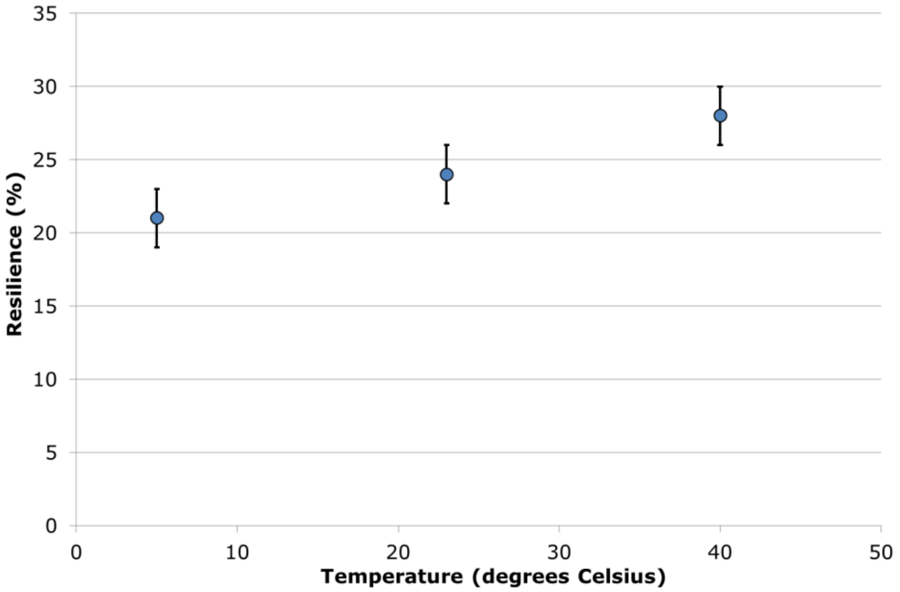

Figure 5-1: The effect of temperature on resilience adapted from data from (The UK Slip Resistance Group, 2016)

Measurements of tyre resilience and skid resistance reported in (Hosking & Woodford, 1976) demonstrated a change in skid resistance with changes in test tyre resilience of 5%. There is the potential therefore for changes in skid resistance to be observed with changes in temperature and this is an effect that has been observed on other sliders used in PSRT testing for other applications for which temperature correction procedures are available.

No temperature correction is as yet available for slider 96 (the slider required for slip resistance testing) and so to mitigate the risk of measurements being affected by temperature it is prudent to apply temperature limits for testing.

It is recommended that a temperature range of 5ºC to 40ºC be observed when making measurements for the assessment of bus floor slip potential[4].

5.3 Conducting the test, characterisation of dry slip resistance

The test sequence presented on page 13 of the UKSRG guidelines requires testing to be carried out at an initial direction and then at 45 degrees and 90 degrees orientation to that direction. For the assessment of bus flooring however this may not always be possible owing to the confinement of space in some locations on buses.

It is recommended that measurement be made in all three directions if possible and a single direction where space constraints dictate.

5.4 Conducting the test, calculating the average PTV

Steps 9 and 10 of the testing procedure listed on page 14 of the UKSRG guidelines state that 8 individual measurements of Pendulum Test Value (PTV) should be made in a single test sequence, and that the median of the last five measurements be calculated as the average PTV for that sequence of measurements. This methodology allows for large variations in measurements and does not necessarily characterise the prevailing skid resistance of the surface. Other standards pertaining to the use of the PSRT require measurements to be repeated until the range of the last five measurements is 3 units or less, and the mean of these values represents the average PTV. This is the methodology stated in BS EN 13036-4 (British Standards Institution, 2011) and the result is that large variations in values are omitted and the nominal skid resistance of the surface is characterised.

It is recommended that during one test sequence, repeat measurements are made until the range of five consecutive measurements is three units or less and the mean of these 5 measurements calculated as the average PTV.

5.5 Slip potential characterisation

The UKSRG guidelines provide criteria for the slip potential of “able bodied, working aged people” walking “in a straight line on a level surface”, these have been replicated in Table 5-1.

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[4] This is the temperature range stated in BS EN 13036-4 (British Standards Institution, 2011).

Table 5-1: Slip potential classifications (The UK Slip Resistance Group, 2016)

Slip potential	Mean PTV
High	≤24
Moderate	25 – 35
Low	≥36

Manufacturers for the majority of surfaces typically used as bus flooring materials state that their products meet the requirement for low slip potential (Section 4). However, it should be noted that these requirements are only valid for the constraints provided in the UKSRG guidelines[5]. These caveats do not apply to the majority of situations involving buses where:

- The vehicle is often in motion
- High risk areas such as stairs prevail
- There are often contaminants on the surface such as mud and water
- People of all ages and abilities may be present

Owing to these considerations it is prudent to adjust the slip potentials stated in Table 5-1 to reflect the unique circumstances that arise on buses. The literature surrounding flooring slip resistance requirements in higher risk areas, or areas where dynamic movement (such as a moving vehicle) is sparse.

The most relevant literature on the subject is detailed in the CIRIA document "Safer Surfaces To Walk On" (Carpenter, Lazarus, & Perkins, 2006). This document recognises the limitation of the work leading up to the generation of the slip potential classifications reported in the UKSRG guidelines. The document states that unless all of the caveats applied to the slip potential characterisations are met (Able bodied, working age people walking in a straight line on a level surface) then the required PTV for the same risk of slipping should be increased appropriately.

Research supporting the augmentation of the slip potential categories has been carried out for the case of walking on sloped surfaces only. The CIRIA document provides a methodology for augmenting the PTV required for low slip risk based on the angle of surface inclination. This procedure is presented in Equation 5-1.

---

[5] Able bodied, working age people walking in a straight line on a level surface

$$Increase\ in\ PTV = 100 \times Tan(\theta)$$

Where:

- Increase in PTV = The amount that the risk category classification should be increased by as a result of the inclined surface (PTV)
- θ = the angle of inclination of the slope (degrees)

Equation 5-1: Augmenting the slip risk categories based on the angle of inclination of a surface

For example, an adjustment based on an angle of inclination of 5 degrees to the low slip category would result in a PTV requirement of 44.7[6].

It is recommended as part of this work that the slip potential categories be augmented in a similar way to better reflect the increase in risk of slipping on buses. In the absence of supporting research, a reasonable increase of 10 PTV (the width of one risk band) is appropriate. This is shown in Table 5-2.

Table 5-2: Updated slip potential classifications for bus flooring

Slip potential	Mean PTV
High	**≤35**
Moderate	**36 - 45**
Low	**≥46**

To add context to the augmented slip potential classifications it can be observed that an increase of 10 PTV would equate to adjusting the slip potential bands for a surface with an angle of inclination of 5.7 degrees[7]. The physical reason why an increased PTV is required to maintain slip potentials on slopes is due to the increase in the acceleration due to gravity parallel to the slope experienced by the pedestrian. With this in mind on a slope of 5.7 degrees the acceleration due to gravity can be calculated using Equation 5-2.

---

[6] Tan(5) = 0.087 x 100 = 8.7. Low slip potential category = 36, adjusting for angle = 36 + 8.7 = 44.7 degrees

[7] $Tan^{-1}(10/100)$ = 5.7 degrees

$$a = g \times Sin(\theta)$$

Where:

- a = the acceleration due to gravity parallel to the surface (m/s^2)
- g = the natural acceleration due to gravity (9.81 m/s^2)
- θ = the angle of inclination of the slope (degrees)

Equation 5-2: Calculating the acceleration due to gravity on an inclined surface

In the case of a slope with an angle of inclination of 5.7 degrees this would equate to an acceleration due to gravity of 0.97 m/s^2 [8]. Given that in the case of an inclined surface, this acceleration is acting parallel to the surface, this case is directly comparable to that of an accelerating (or braking) vehicle where the acceleration due to the change in vehicle speed is also acting parallel to the surface.

TRL report SR520 presents acceleration data collected on a number of bus vehicles and states that typical bus acceleration/ braking values are between 1.47 m/s^2 and 4.21 m/s^2. Comparing these typical bus performance values with the 0.97 m/s^2 adjustment that is recommended for the slip risk bands shows that the recommended adjustment is modest and reasonable.

It is recommended that the slip potential is characterised using the values stated in Table 5-2, rather than those stated in the UKSRG guidelines.

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[8] a = 9.81xSin(5.7) = 0.97m/s^2

6 Full scale assessment of bus flooring materials

This section seeks to apply the testing methodology derived in the previous section 5 to a sub-section of the TfL bus fleet. The aims of this testing are to:

- Understand if the derived test methodology is appropriate for buses.
- Understand the nominal skid resistance performance of traditional bus flooring materials.
- Understand how the skid resistance performance of these materials changes with time and pedestrian footfall.

6.1 Test apparatus

The PSRT has been identified as the most appropriate device for characterising slip resistance, and the UKSRG guidelines (with some subtle augmentation) the most appropriate guide for characterising slip potential. The testing therefore focussed on measurements made using the PSRT which was carried out, in situ, on flooring materials installed on new buses and those that have been in operation for some time.

6.2 Materials assessed

The review of literature pertaining to available flooring materials (section 4) identified 13 materials used for bus flooring, manufactured by 5 companies. The purpose of the proposed testing was to demonstrate that the proposed testing methodology is applicable to the surface materials, is sensitive enough to identify those materials that offer the highest and lowest slip resistance, and to identify general trends in material performance over time.

Carrying out testing on all 13 materials would have been unnecessary for this purpose, and operationally prohibitive. The 12 materials can be grouped into the following categories:

- Mineral Encapsulated Composite (MEC). Products, 2A, 1B, 2C and 1E.
- Smooth Vinyl. Products, 1A, 2B and 2E.
- Textured vinyl. Product 3B.
- Rubber bonded cork. Products,1D and 2D.
- Fabric. Product 3E.
- Transparent layer with “anti-slip” particles. Products, 3A and 1C.

Fabric materials are unsuitable to be assessed with the PSRT and it is understood that materials utilising a transparent layer with anti-slip particles are not used on London buses. Testing therefore focussed on characterising the overall performance of MEC, smooth vinyl and textured vinyl materials.

The “as new” performance of these materials is well documented but no information could be found relating to the performance of the materials with time and wear. The testing therefore focussed on characterising the slip resistance performance of these material types in service. It was requested that materials were assessed in an “as cleaned" condition. However observations made on site made it clear that this was not always the case.

6.3 Vehicles assessed

The vehicles to be assessed were selected using data supplied by TfL (Transport for London, 2017). It was endeavoured to identify three different bus types, and one example of each bus type at three different ages. The following criteria were used to select the buses for assessment:

- At least one bus type should contain either, MEC, Smooth Vinyl or Textured Vinyl materials.
- At least one bus type should be a single decker vehicle and at least one bus type should be a double decker vehicle.
- The buses selected within a single type should represent a good spread of service lives and/or approximate total footfall.
- All buses of a single type should be from the same route, and preferably stored and maintained by the same operator and garage.

Table 6-1 summarises the buses that were selected from the search.

Table 6-1: Summary of buses assessed

	Bus identifier								
	A-1	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
Age (years)	1	5	7	0	3	3	1	5	6
Approximate total footfall (millions)	0.21	0.48	1.21	0.21	0.59	0.64	0.25	1.51	2.02
Route number		80		EL1	148	9		432	
Materials assessed		MEC and Smooth Vinyl			MEC and Grooved Vinyl			MEC, Smooth Vinyl & High Friction Tape / MEC	

Table 6-1 shows that Bus A and Bus C fulfil the criteria well, however the only bus identified as using a textured vinyl material was Bus B. Bus B is a relatively new design having been accepted into the TfL fleet in the last 3 years. Naturally, no examples of this vehicle over 3 years old could be identified.

The approximate total footfall for each bus was calculated from usage data provided by TfL. These data gave the total annual footfall for each route on the TfL bus network over the previous 6 years. Data detailing the number of vehicles servicing each route were also made available. Equation 6-1 was used to calculate the annual average footfall for any given bus on each of the routes operated by TfL.

$$Approximate\ total\ footfall = \sum_{x=0}^{a} \left(\frac{F_x}{\sum_x^a B_x} \right)$$

Where:

- a = Age of the bus (years)
- x = Time from current date (years)
- F_x = Footfall for route in year x (integer)
- B_x = Number of buses on route in year x (integer)

Equation 6-1: Calculation of approximate total footfall

Figure 6-1 presents the cumulative distribution of annual average footfall for each **vehicle** on the TfL network. The red broken line represents the range of average annual footfall observed in the buses assessed. Figure 6-1 shows that the buses assessed represent between 50.0% and 99.5% of all the buses operating on the TfL network. Whilst 99.5% of buses on the TfL network have an average annual footfall of approximately 2 million, there are some exceptions where buses are carrying over 7 million passengers per year.

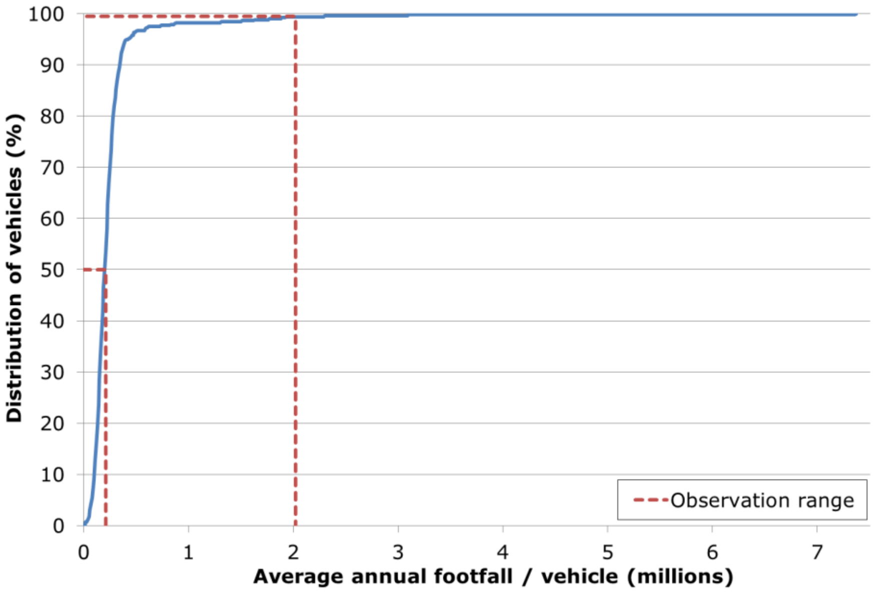

Figure 6-1: Distribution of the number of vehicles operating with different annual average footfalls

Figure 6-2 shows the distribution of **passengers** carried on buses with different approximate annual footfalls. This visualisation shows that the vehicles assessed represent between 30% and 90% of the passengers carried by TfL every year.

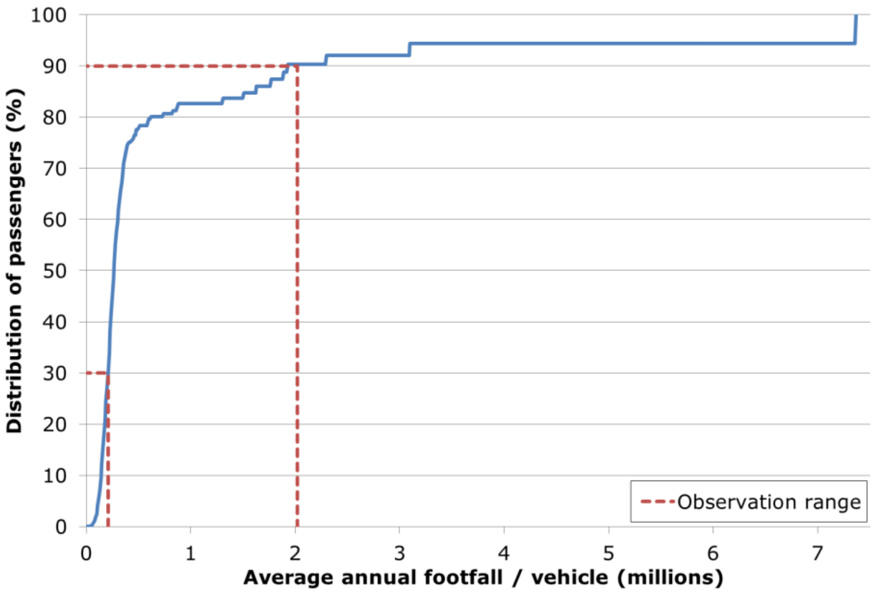

Figure 6-2: Distribution of the number of passengers carried by buses with different annual average footfalls

Whilst it would be interesting to conduct these assessments on buses carrying circa 7 million passengers per year, a detailed investigation of the bus usage data revealed that there is only one bus on the TfL network which carries more than 3 million people / annum. This behaviour is therefore an outlier and could be related to a counting error in the data. Removing this potential outlier from the data revealed that the buses assessed account for between 30% and 95.6% of the passengers carried by TfL every year.

6.4 Test locations

It was endeavoured to characterise the slip resistance properties of each bus in the following locations:

- Each of the entrance ways, the most highly trafficked areas.
- The area next to the driver’s cabin.
- At least one “low risk” location in the aisle, that is, areas that are flat and not associated with priority seating, doors or steps.
- Every “high risk” location in the bus cabin, e.g. stairs, areas in front of priority seating, doorways, etc…
- In each location measurements were made in three directions as stated in (UK Slip Resistance Group, 2016) except in those instances where this was not allowed by the bus geometry.

Figure 6-3, Figure 6-4 and Figure 6-5 show the locations of measurements made in each of the buses assessed. The type of material in each location has also been presented; the shape and colour of the identifier in each image are related to the series markers in the results charts.

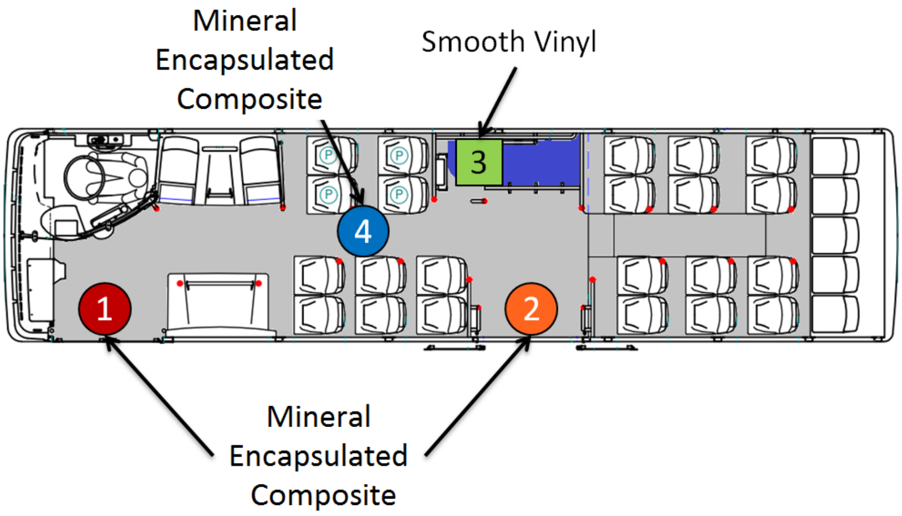

Figure 6-3: Test locations, Bus A

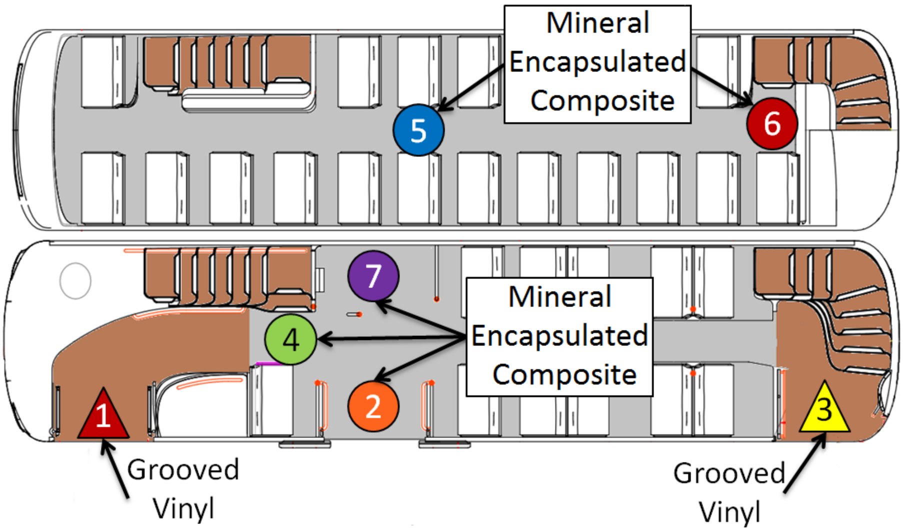

Figure 6-4: Test locations, Bus B

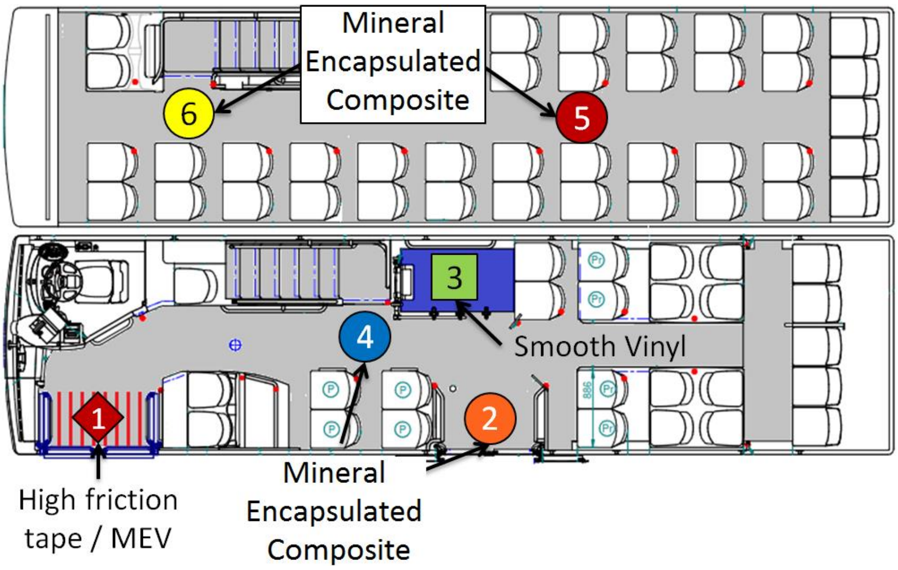

Figure 6-5: Test locations, Bus C

6.5 Results & Key Findings

This section presents the results of the testing regime, data are presented for each bus assessed and general observations made regarding each material type. Because of the granularity of the data it has been possible to draw general qualitative conclusions only. The quantitative aspects of these observations will require further extensive study outside of the scope of this work.

6.5.1 Bus A

The results of measurements made in Bus A are presented in Figure 6-6. The x-axis of Figure 6-6 represents the approximate total footfall that the surface has been exposed to. The y-axis presents the average mean PTV calculated for each location which is represented by the various series. Measurements made in dry conditions are presented with faded series markers as the pertinent data from a safety aspect are related to those measurements made in wet conditions. The categories of slip risk from Table 3.6 have been included in this figure for ease of interpretation.

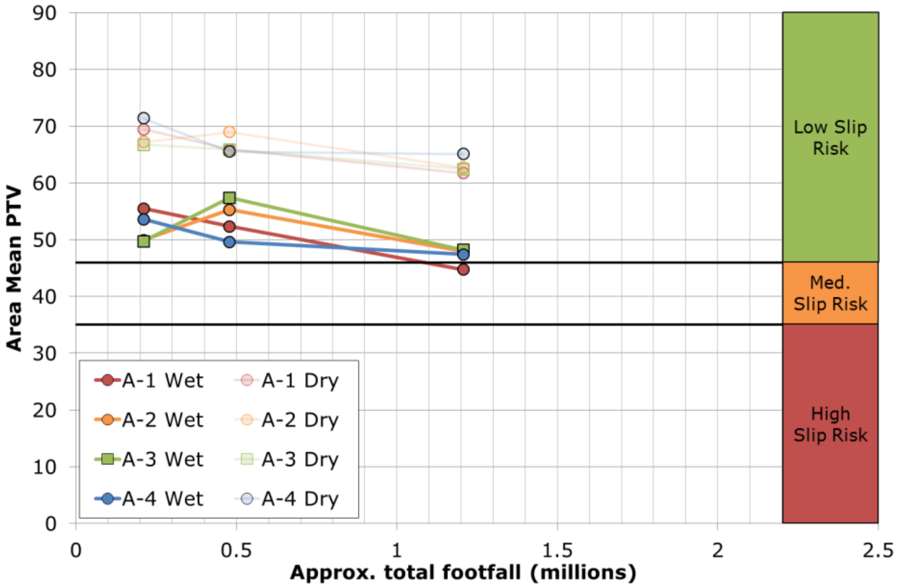

Figure 6-6: Results collected from Bus A

Figure 6-6 shows that all but one of the measurements made are providing slip resistance levels in the low slip risk category. Measurements made on A-1 at 1.2 million footfall are just inside the medium slip risk category. Position A-1 was inside the front door of the vehicle and so this position may have a slightly higher footfall than other areas such as A-3, the wheelchair reservation area.

All of the materials displayed a slight reduction in slip resistance with footfall. For locations A-2 and A-3 this occurred after an initial phase of improvement, whereas locations A-1 and A-4 showed a continual decline. This difference in performance could also be attributed to the variation in footfall in various locations in the bus.

6.5.2 Bus B

The results of measurements made in Bus B are presented in Figure 6-7 and Figure 6-8. Figure 6-8 presents data pertaining in to measurements made at different angles on the grooved vinyl material. The x-axis in Figure 6-8 shows the angle of measurement perpendicular to the groove direction, an image of the direction is also shown for clarity. The y-axis shows the mean PTV for each set of measurements. The series represent the two locations in each of the three buses that contained grooved vinyl.

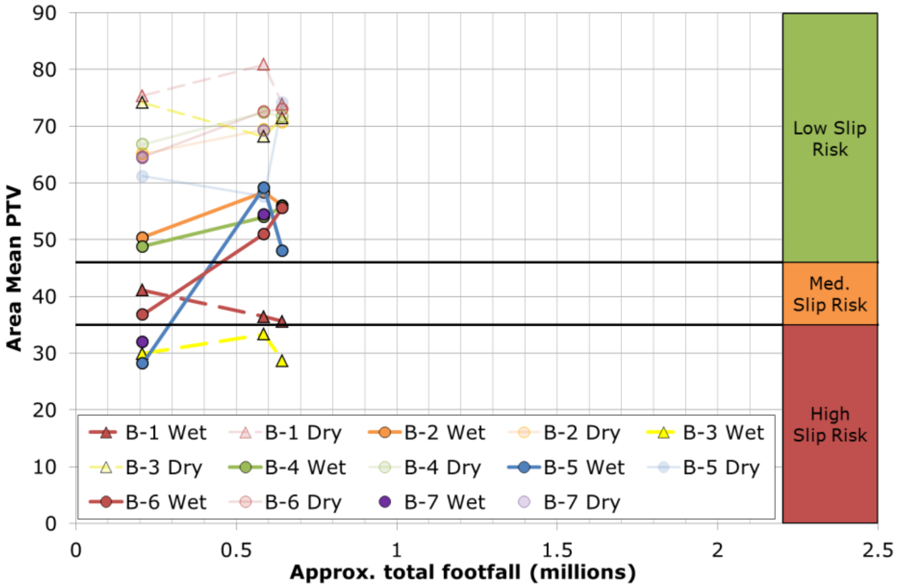

Figure 6-7: Results collected from Bus B

Figure 6-7 shows that after 0.6 million footfall all of the MEC materials are providing a performance within the low slip risk category. As with Bus 1 there is a variation in performance characteristics with the MEC materials. Whilst all MEC materials show an increase in performance, the improvement in measurements made in locations B-5 and B-6 is markedly greater than that observed for locations B-2 and B-4.

The grooved vinyl materials are, overall, providing a poor wet slip resistance. These materials (locations B-1 and B-3) provide the highest levels of dry slip resistance and the lowest levels of wet slip resistance. Levels at the rear door (location B-3) are consistently lower than the high risk threshold. To investigate this material further an analysis of the directional effects of the surface was carried out and is presented in Figure 6-8.

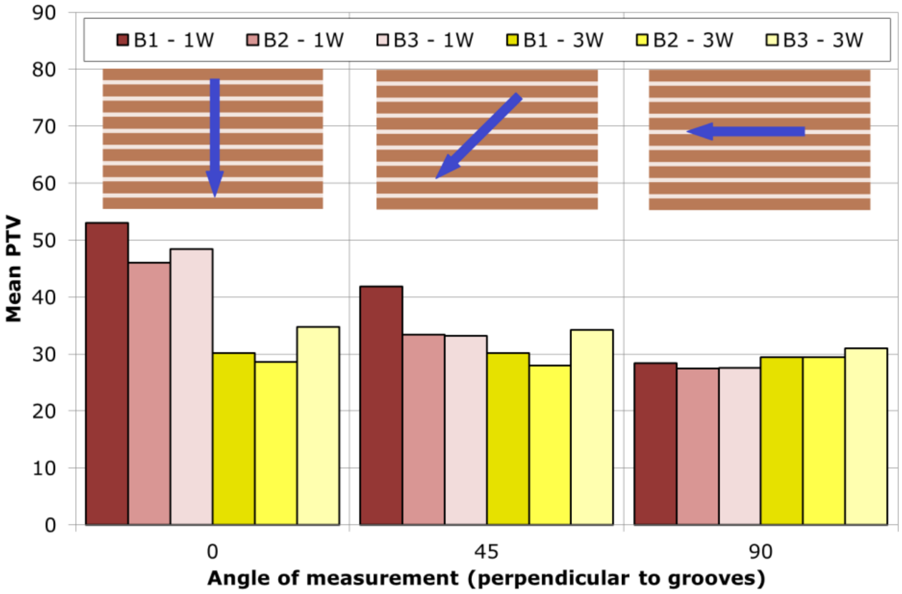

Figure 6-8 The effect of test angle on slip resistance

Figure 6-8 shows that the performance of the grooved vinyl material is different in location B-1 than location B-3, this is likely due to a subtle difference in the grooving pattern at each location. The best performance is observed in location B-1 for measurements made perpendicular to the grooving direction. However these measurements are only within the medium slip risk category. Measurements made in location B-3 are all within the high slip risk category.

6.5.3 Bus C

The results of measurements made in Bus C are presented in Figure 6-9.

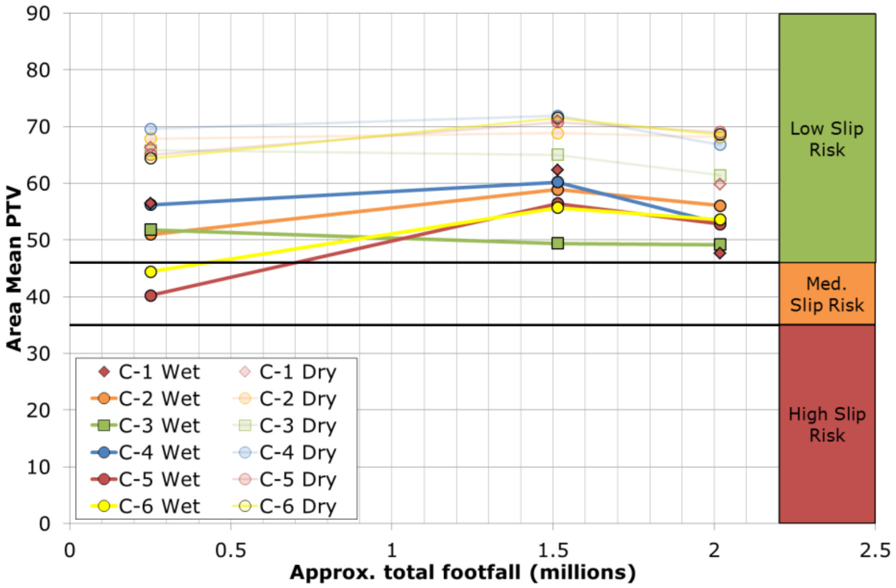

Figure 6-9: Results collected from Bus C

Figure 6-9 shows that all but two measurements made are in the low slip risk category. An improvement in slip resistance is observed on all of the EAC materials between 0.25 and 1.50 million footfall after which a subtle decline in performance is observed. A continual decline in performance is shown on the smooth vinyl material.

The high friction tape / MEC material provides the highest levels of wet slip resistance at 0.25 and 1.50 million footfall. Measurements made with this material at 2.00 million passes were conducted on a material contaminated with a mixture of oil and water. Despite this, the performance of this material remained in the low slip risk category.

6.6 Summary and Conclusions

6.6.1 MEC materials

Considering all of the measurements made it can be concluded that the MEC materials performed well and in general provide levels of wet slip resistance in the low risk category.

On some of the materials assessed an initial period was observed where the performance of materials improved. It is hypothesized that this is a result of the material wearing in response to footfall and/or aging which exposes more of the embedded material offering improved slip resistance performance. This effect is also common on some road surfacings where it is related to the wearing of bitumen from aggregate particles.

After this period of improvement, all of these surfaces showed a reduction in slip resistance with footfall. The surfaces not demonstrating an initial period of improvement showed a continual decrease in performance.

6.6.2 Grooved vinyl materials

The grooved vinyl materials were not able to achieve the same performance as the MEC materials or smooth vinyl materials. In the absence of other supporting evidence for the use of these materials it is recommended that grooved vinyl materials are systematically replaced with MEC materials. It may be possible to develop a grooved MEC material with a similar aesthetic to the grooved vinyl material and this should also be investigated.

6.6.3 High friction tape / MEC

The combination of MEC and high friction tape materials performed well and provided the highest wet slip resistance values of all the materials assessed. This combination of materials provided slip resistance values in the low risk category even when contaminated with oil and water. This combination of materials may provide a good solution for the provision of slip resistance in high risk or high traffic areas.

6.6.4 Smooth vinyl materials

The smooth vinyl material performed similarly to the MEC materials on Bus A but displayed a clearly different performance to the MEC materials on Bus C. The overall performance of this material could therefore be classified as good. The same performance characteristics as the MEC material was observed on Bus A, an increase in performance followed by a reduction, which may suggest that this material is also subject to a wear in period.

6.6.5 Next steps

The next steps for this work following the findings of the testing are summarised below:

- Investigate polishing or sanding method to improve slip resistance performance of materials.

- Investigate the use of high grip tape in order to mitigate initial risk.

These investigations were carried out as part of this work and are reported in the next section which details a period of laboratory testing of bus flooring materials.

7 Laboratory assessment of bus flooring materials

This section presents a laboratory study carried out to address the next steps identified from the full scale testing work reported in section 6, namely:

- Investigate polishing or sanding method to improve slip resistance performance of materials.
- Investigate the use of high grip tape in order to mitigate initial risk.

In addition, work was also carried out to measure the initial PTV of a number of bus flooring materials to ascertain if a requirement for a higher PTV in service compared to when new may be practical.

7.1 Method

This section details the laboratory approach taken, this can be summarised as:

- Assessing the “as new” slip resistance of various flooring material specimens, namely:
    - A Mineral Encapsulated Composite (MEC) with vinyl chippings,
    - A Mineral Encapsulated Composite (MEC),
    - A thin wearing layer.
- Applying abrasion techniques to the specimens in an attempt to improve the slip resistance characteristics of the specimens namely:
    - Rotary buffer and grinding paste,
    - Abrasive paper,
    - Grit blasting,
    - The application of high friction tape.
- Simulating bus passenger footfall on each of the specimens and assessing the slip resistance characteristics at different footfall levels.

7.1.1 The specimens

For the purposes of this work, three batches of specimens were assessed, each batch representing a different material type. Sixteen specimens from each batch were used for testing. Three specimens were used for each treatment, and three specimens from each batch were used as control specimens. No treatment was applied to the control specimens, scuffing represents footfall only. Data collected for each batch and treatment was compared with control specimens.

The materials used in this study are presented in the following sub-sections.

7.1.1.1 Mineral Encapsulated Composite (MEC) with vinyl chippings

Mineral Encapsulated Composite with vinyl Chippings is a polyvinyl chloride material embossed with minerals particles throughout the whole depth of the material. The minerals, which are believed to be carborundum, are incorporated to provide slip resistance. MEC with vinyl chippings is one of the more common flooring materials used in the TfL bus fleet.

7.1.1.2 Mineral Encapsulated Composite (MEC)

The surface of MEC is comprised of an un-textured polyvinyl chloride. Mineral Encapsulated Composite materials were assessed as part of the full scale testing reported in section 6.

7.1.1.3 Thin wear layer

Thin wear layer materials are becoming more popular in bus design owing to their aesthetic properties. Materials classified as thin wear layer are comprised of a printed material covered by a thin transparent wear layer which contains microparticles that provide the material with its slip resistant properties.

7.1.2 The abrasion techniques

The hypothesis standing behind each of the abrasion techniques used in this study is to remove a thin top layer from the specimens and, in the case of the MEC materials, expose the mineral particles that are responsible for providing slip resistance. The methods of abrasion used in this study were chosen as they represent methodologies that are relatively simple to apply and can be achieved in situ or during manufacturing process.

7.1.2.1 Rotary buffer and grinding paste

Commercially available grinding paste (similar to that used in the grinding of internal combustion engine components) and a rotary polisher (similar to that used in the polishing of car bodywork) was used to abrade the specimens.

The abrasion process was carried out by applying grinding paste to the head of the polishing buffer and abrading the surface with the polishing buffer for a controlled amount of time (for the same amount of time on each specimen). The exact amount of time was determined by the laboratory technician. For practical reasons a polishing time limit of 60 seconds was imposed as this was estimated as the maximum practicable time limit that could be applied to bus floorings in service.

Following the application of this technique the specimen was gently washed with water to remove any abrasive paste which could influence the slip resistance measurement.

7.1.2.2 Grit Blasting

A grit blasting device[9] was used to abrade the specimens using high pressure air (5 bar) to propel grit (natural aggregate material with a nominal size of 1 mm) over the surface of the specimens.

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[9] The normal function of which is to remove bitumen from the surface of asphalt laboratory specimens.

The nozzle[10] of the grit blaster was fixed inside the device and the technician moved the specimen underneath the nozzle in a controlled way to ensure the surface was blasted evenly. In similar way to the other techniques each specimen was grit blasted for the same amount of time, 7 seconds.

Following the grit blasting process specimens were wiped with a damp cloth to remove any detritus or dust that could have affected the slip resistance measurement.

7.1.2.3 Abrasive paper

The specimens were abraded using a P80 abrasive paper with silicon carbide particles with size 201$[\mu m]$ in FEPA scale. The abrasive paper was installed on a random orbital sander to control the abrasion process and specimens were abraded for 30 seconds. Polishing movements were applied as shown in figure 7-1 and a minimum downward pressure was applied to the sander during the abrasion.

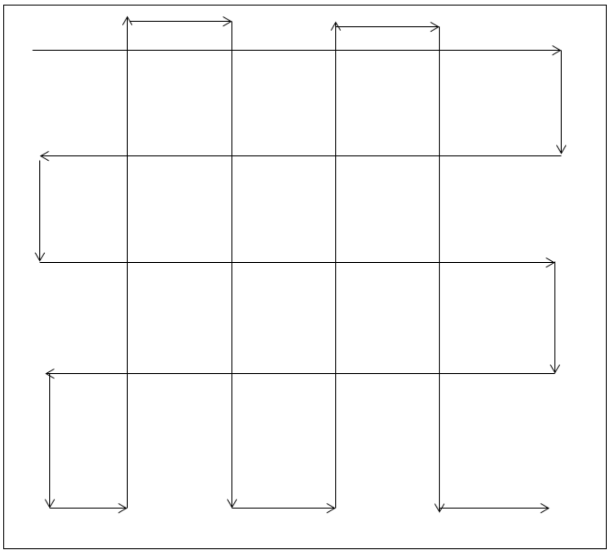

Figure 7-1: Sequence of polishing movements

7.1.2.4 High friction tape

The application of high friction tape (as a traditionally used on the nosing of stairs) was investigated as an alternative methodology for reducing slip risk on buses. High friction tape was applied to the materials assessed under the following conditions:

- The tape was 50 mm wide,
- the tape was installed at a 45 degree angle to the direction of scuffing,
- strips of tape were placed no more than 35 mm apart.

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[10] Internal diameter of the nozzle = 7 mm

An example of this is shown in Figure 7-2.

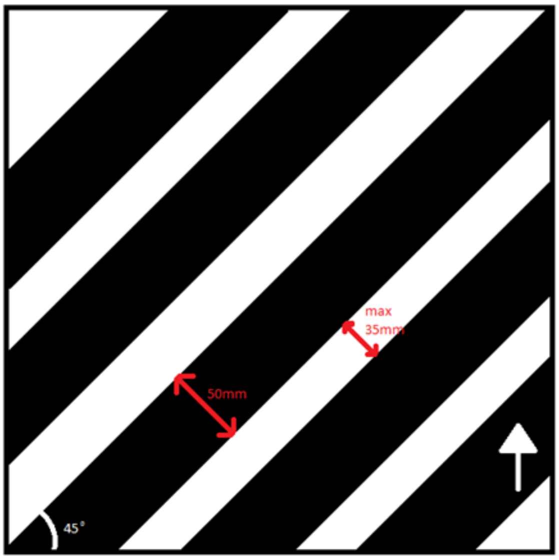

Figure 7-2: Scheme of high friction tape applied on a speciemen.The white arrow indicates direction of travel.

7.1.3 Simulating footfall

The simulation of footfall was carried out using the Wheel Tracking Machine (WTM). The primary function of the WTM is to simulate vehicular trafficking wear on road surface materials. The procedure for that test is detailed in TRL Report 176 (Nicholls, 1997). For the purposes of this study the WTM was set up in the scuffing configuration. The scuffing configuration consists of a loaded wheel (700 N) which bears on a specimen held on an oscillating moving table. The table reciprocates beneath the wheel with the axle of the wheel held at an angle of 20 ± 1 degrees to the direction of travel.

To compare the impact of the WTM on the specimens with that of pedestrian footfall, the typical foot / floor pressure of pedestrians was compared with the pressure between the WTM wheel and a flat floor. This analysis is presented below.

$$P_1 = \frac{F}{a} = \frac{757.8}{0.0059} = 0.128\ MPa$$

Where:

- P_1 = the average pressure between a pedestrian and a flat surface (MPa)
- F = the average force between a pedestrian and a flat surface (Newtons) (www.onaverage.co.uk, n.d.)
- a = the average area between a pedestrian footprint and a flat surface (m^2) (Chi-Yuang Ya, Hsin-Hung Tu, 2008)

Equation 7-1: The average pressure between a pedestrian foot and a flat surface

$$P_2 = \frac{F}{a} = \frac{700}{0.0012221} = 0.573\ MPa$$

Where:

- P_2 = the average pressure between the WTM wheel and a flat surface (MPa)
- F = the force applied to the WTM wheel (Newtons)
- a = the area between the WTM wheel and a flat surface (m^2)

Equation 7-2: The pressure between the WTM wheel and a flat surface

Equation 7-1 and Equation 7-2 demonstrate that the WTM applies approximately 4.6 times more pressure than that of an average person. For this reason the WTM was considered suitable for this study. Based on these figures the equivalent footfall was calculated for the WTM based on the number of passes applied to a specimen in the WTM, this is shown in Table 7-1.

Table 7-1: Equating passes to approximate equivalent footfall

Passes	Approximate equivalent footfall
0	0
50	230
100	460
250	1150
500	2300

Trafficking up to 0.5 million equivalent footfall is ideal but it is outside the design capabilities of the WTM. Instead 500 passes was chosen as this is the practicable maximum of the WTM within the context of this study.

7.1.4 The characterisation of slip resistance

Slip resistance in this laboratory study was characterised using the same methodology as that used in the full scale testing (section 5 and section 6) with one exception. Owing to the small area affected by the WTM foot a smaller version of the pendulum foot to that used in the full scale study was used. So that the measurements made with the smaller pendulum foot could be compared to those made using the larger pendulum foot (during the full scale testing), a correction factor was calculated using data collected from testing the control specimens alternately with the small and large rubber sliders. The results are therefore presented with this correction factor applied.

7.2 Results

The results of the testing are presented in this sub section. Results are presented graphically each abrasion technique (and unabraded control specimens) in the following sub-sections. Each figure presents the mean PTV at the different simulated footfall levels (the series markers), and the range of Equivalent PTV measurements made (the error bars). The primary x-axis of the figures represents the actual amount of trafficking applied to the specimens in terms of the number of passes applied in the WTM. The secondary x-axis presents an approximation as to the amount of footfall this would equate to in a real-life scenario.

7.2.1 Control specimens

Figure 6-6 shows the control specimens' behaviour (control specimens were trafficked only, no treatment was applied). The MEC with vinyl chippings materials are showing the highest equivalent mean PTV compared to other materials. Furthermore, these materials are demonstrating the greatest improvement in slip resistance in response to the trafficking. This suggests that the trafficking had a positive influence on the slip resistant silicon carbide particles. This observation concurs with some of the full scale measurements made which demonstrated a similar initial behaviour with footfall.

Figure 7-3 demonstrates that the thin wear layer was firstly polished resulting in a reduction in slip resistance, followed by a recovery in slip resistance to approximately 27 PTV value after 400 passes (1,840 footfalls).

There were no substantial changes in the performance of the MEC with vinyl chippings.

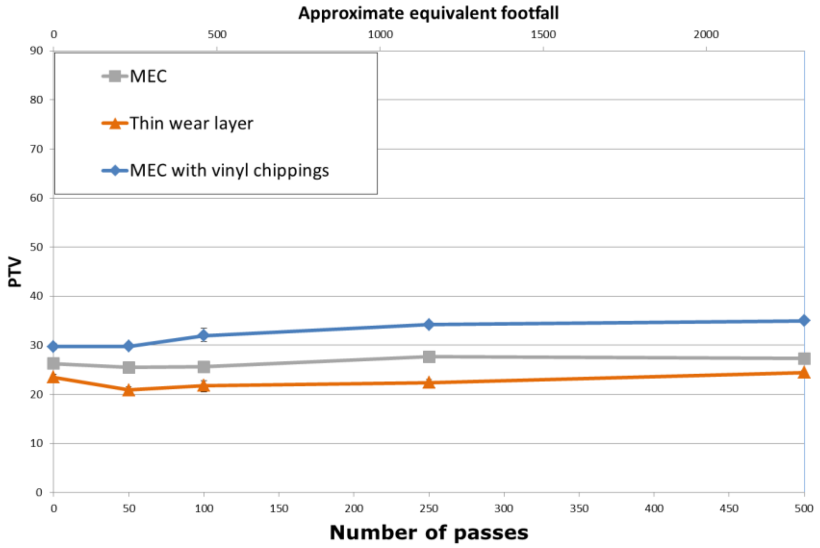

Figure 7-3: Control specimens

7.2.2 Rotary buffer and abrasive paste

This method of abrasion showed a negligible change in skid resistance for all of the materials tested. Applying abrasive paste even for more than 60 seconds and applying substantial pressure didn`t provide a change in slip resistance value. The PTV values instead of increasing decreased or stayed as before the treatment. After a few tests this method was therefore abandoned.

What can be learned from this methodology is that the abrasive paste worked as a polishing medium and something with a markedly greater abrasive power was needed to observe a difference in PTV.

7.2.3 Grit blasting

The result of measurements collected for the grit blasting process are presented in Figure 7-4. Comparing mean PTV between the control and treated specimens, it is observed that a substantial increase in PTV was produced on all materials following treatment. The mean PTV rises for each material with trafficking, this is expected for the MEC with vinyl chippings material which demonstrated this behaviour on the control specimen. For the MEC and Thin wear layer however, this behaviour is markedly different to the control specimens, suggesting that the grit blasting has a substantial effect on these material types.

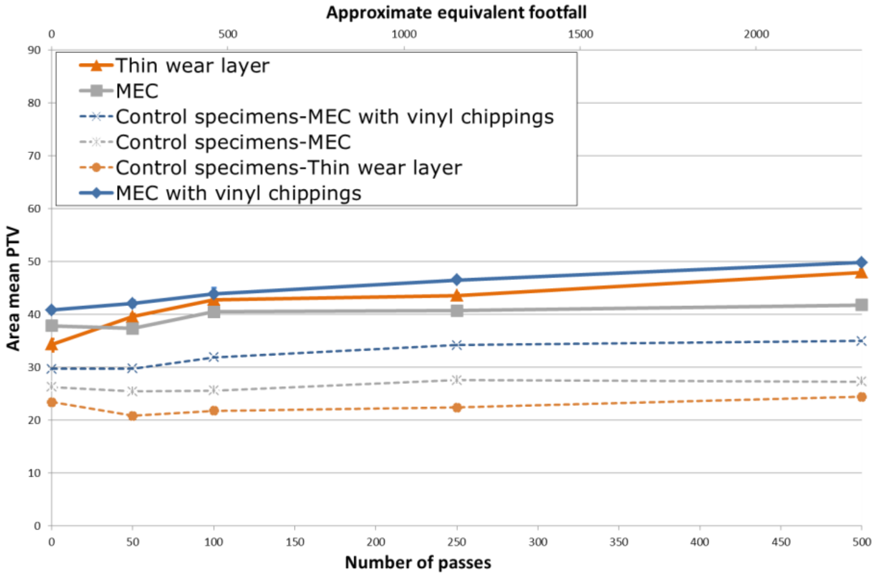

Figure 7-4: Wet mean PTV for grit blast specimens and control specimens

7.2.4 Abrasive paper

The results of measurements made with the abrasive paper are presented in Figure 7-5. As with the grit blasting technique an increase in PTV is observed on all materials in comparison to the control specimens.

The greatest change in behaviour was observed on the Thin Wear layer which showed a continual increase in PTV between 0 and 250 passes. The control specimens however displayed a small decrease followed by a small increase in PTV.

The MEC displayed an overall increase in slip resistance with trafficking but also showed a decrease in PTV at 250 passes. It is possible that this could be due to experimental error but this is unlikely given that the error bars demonstrate a relatively consistent measurement performance.

Mean PTV for MEC with vinyl chippings increased between 0 and 50 passes, after which values remained stable. It is noteworthy that the PTV at 0 passes was the same as measured on the grit blasted specimens after 250 passes. This suggests that the abrasive paper produced a greater effect on the specimens than the grit blaster.

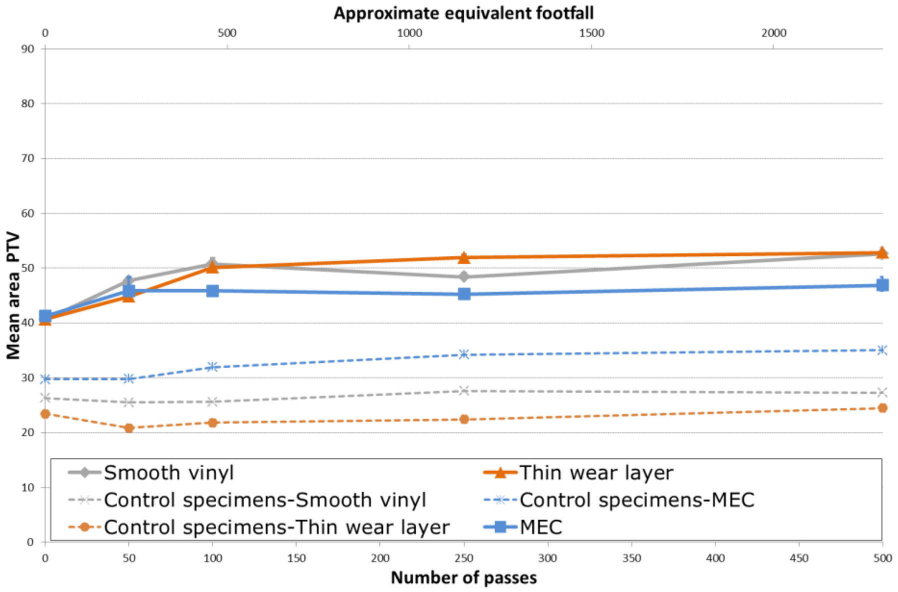

Figure 7-5: Equivalent mean PTV for specimens treated using P80 and control specimens comparison.

7.2.5 High friction tape

Mean PTV measurements made on materials with high friction tape applied are shown in Figure 7-6. The number of passes applied in this method didn`t reach more than 100 passes because the high friction tape was peeled off by the scuffing wheel. This suggests that under heavy wear conditions, the tape is unlikely to stay bonded to the surface.

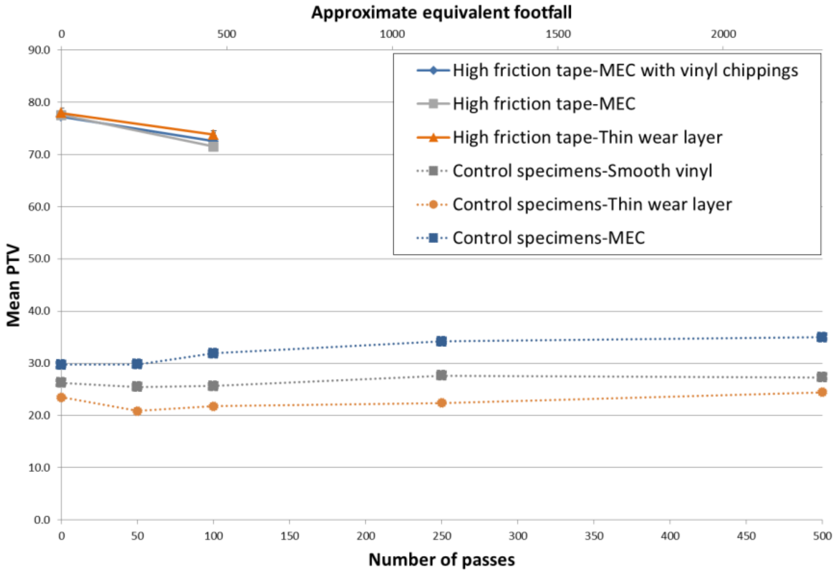

Figure 7-6: Specimens behaviour with high friction tape applied

7.3 Summary and conclusions

7.3.1 *The use of abrasion techniques*

The assessment demonstrated that the use of abrasion techniques has the ability to substantially increase the slip resistance properties of typical bus flooring materials. However, the assessment has also shown that the amount of trafficking applied on the specimens was insufficient. Comparing PTV values after 2.300 footfall to full scale testing where floors were tested on average after 0.5 million footfall is difficult and long life behaviours of assessed materials cannot be estimated.

In most cases equivalent mean PTV after trafficking above 40 was observed, achieving the requirement for low slip risk when in service. However, this was only observed in the cases where highly aggressive methods of abrasion were used.

7.3.2 *The use of high friction tape*

The application of high friction tape produced the greatest increase in PTV observed, but the duration of this improvement is called into question as the tape was only viable for a limited amount of trafficking.

7.3.3 *The initial performance of bus flooring materials*

Data collected during the laboratory assessments has shown that new materials have a PTV between 25-35. The UKSRG state that the PTV value for low slip resistance is equal or greater than 36. This suggests that it would not be possible for these materials to meet the minimum criteria for low slip resistance. It should be noted however that materials with a PTV of >36 PTV are commercially available. Primary evidence for this was collected following the laboratory assessments.

8 Cost-benefit analysis

The cost-benefit analysis (CBA) presented in this section seeks to quantify the financial benefit or cost of implementing the proposed solutions. This is achieved by estimating the number of casualties mitigated by the proposed solution and by extension the total value of these casualty reductions to society. The value to society of the casualty reductions is then compared to the cost of the solution to determine if the solution is providing a financial benefit, or cost. Further information on the general approach adopted by the CBA may be found in Appendix A.

8.1 Summary of proposed solution

A CBA was carried out to quantify the benefits of a solution designed to address the Non-Slip Flooring (NSF) measure of the bus safety standard. The solution proposed is to replace the flooring materials of buses utilising grooved vinyl materials with mineral encapsulated composite materials. Grooved vinyl was identified as providing low levels of slip resistance, and therefore, high levels of slip risk. It is proposed to replace those areas of flooring that are affected only negating the need to replace the flooring in its entirety.

To this end, and for the purposes of this work, a new build solution is defined as a replacement of the floor or part of the floor during the normal servicing process where the entirety of the bus floor would be replaced as a matter of course. A retro-fit solution is defined as the replacement of part of the floor at any other time.

8.2 Target population

The target population for the NSF measure was derived from interrogating the IRIS database. The target population was limited to those persons who have slipped within the bus cabin and sustained an injury as a result of a wet floor. Dry flooring slips were ignored as previous works have shown that bus flooring materials provide more than adequate slip resistance values to reasonably mitigate slip risk in dry conditions.

The annual target population in the year 2014 to 2017 was estimated using information contained in the IRIS database. The following filters were used to identify the target population:

- Primary Incident Event Type = Slip trip or fall
- Wet = Wet
- Injury Sustained = Yes
- Immediate cause = poor / slippery / surface

This analysis returned a total of 19 results, all of which were identified as taking place in the bus cabin for standing bus occupants only.

Because of the limited amount of data returned by this query, a robust estimate of the typical distribution of these figures amongst Fatal, Serious and Slight injury could not be made. To this end a larger set of the IRIS database was assessed. This included data recorded between 2015 and 2016 relating to all bus occupant casualties who were standing, involved in collision or non-collision incident. In addition a range of +/-

5% was applied to allow upper and lower ranges to be calculated. This analysis returned the following distribution of casualties, with annual target population values shown in Table 8-1:

- Fatal – 0% to 0%
- Serious – 6% to 17%
- Slight – 78% to 100%

Table 8-1: Estimated average annual target population in 2018 for the Non-Slip Flooring [NSF] safety measure solution

Safety Measure Solution	Injury Severity		
	Fatal Casualties	Serious Casualties	Slight Casualties
NON-SLIP FLOORING	0	0.3-1.0	4.7-6.0

8.3 Estimates of effectiveness

The relationship between flooring slip resistance and incident risk was not identified in any literature reviewed. To this end effectiveness values were derived from the opinion of TRL experts. For the purposes of this work it has been assumed that flooring with improved slip resistance should have an effectiveness of 10% +/- 5% for both serious and slight casualties as shown in Table 8-2. It was assumed that the implementation of the non-slip flooring safety measure solution will only be able to prevent casualties from occurring, not mitigate their severity once a slip has occurred.

Table 8-2: Estimated overall casualties prevented effectiveness ranges for the Non-Slip Flooring [NSF] safety measure solution

Safety Measure Solution	Casualties Prevented		
	Fatal Casualties	Serious Casualties	Slight Casualties
NON-SLIP FLOORING	0%	5-15%	5-15%

8.4 Fleet fitment and implementation timescales

The proportion of the current fleet fitted with flooring that has the desired slip resistance properties was estimated with feedback from the stakeholder consultation (Table 8-3).

The solution for this measure uses current techniques and materials, thus it may be immediately implemented for 2019. With this in mind the implementation timescale for this solution to be fitted across 100% of the TfL fleet is defined as:

- 7 years for new fit solutions, as 7 years is the normal replacement cycle for bus flooring materials, and,
- 2 years for retrofit systems.

Please see associated stakeholder consultation report for further information on the stakeholder feedback for fleet fitment and policy implementation timescales.

Table 8-3: Fleet fitment and policy implementation timescales for Non-Slip Flooring [NSF] safety measure solution

Safety Measure Solution	First to Market	Date Policy Implemented	Current Fleet Fitment (%)	Full Fleet Adoption (yrs)	
				Retrofit	New Build
NON-SLIP FLOORING	2019	2019	85%	2	7

8.5 Casualty benefits

Table 8-4 and Table 8-5 summarise the estimated total change in the number of casualties expected in London during the period 2019-2031 by specifying the performance of new build and retro fit buses respectively for the NSF safety measure solution. Outcomes are then monetised to estimate the total value of these casualty reductions to society.

Table 8-4: Estimated total change in number and value (NPV) of incidents over the 12-year analysis period (2019-2031) for the new build Non-Slip Flooring [NSF] safety measure solution

Safety Measure Solution	Number of Incidents (n)			Value (NPV) of Incidents (£M)s
	Fatal Casualties	Serious Casualties	Slight Casualties	
NON-SLIP FLOORING	0	0.03-0.28	0.44-1.70	0.01-0.09

Table 8-5: Estimated total change in number and value (NPV) of incidents over the 12-year analysis period (2019-2031) for the retrofit Non-Slip Flooring [NSF] safety measure solutions

Safety Measure Solution	Number of Incidents (n)			Value (NPV) of Incidents (£M)s
	Fatal Casualties	Serious Casualties	Slight Casualties	
NON-SLIP FLOORING	0	0.04-0.39	0.60-2.31	0.02-0.12

8.6 Cost implications

The costs of non-slip flooring performance requirements as part of the bus safety standard can be divided into five key cost categories based on:

- Differences in development, manufacturing and certification costs
- Differences in implementation and installation costs

- Differences in ongoing operational costs
- Differences in insurance claims costs
- Differences in environmental and infrastructure costs

Given the nature of the solution, the costs associated with the installation of the new build solution (i.e. the replacement of flooring materials at standard servicing intervals) have been assumed to be zero, given that this activity would be carried out regardless.

Costs associated with the retrofitting of the solution have been calculated from the costs associated from the installation of the materials outside of the standard servicing schedule. Based on the feedback from the stakeholder consultation, the approximate baseline costs associated with the materials and installation costs for retrofitting the entire bus with non-slip flooring was £5,000-7,000 (60% installation costs and 40% materials costs). It has also been assumed that in any given case 80% of the bus flooring would be in sound condition. Therefore the costs associated with retro-fitting apply to the fitment of 20% of the materials only.

The annual changes in incidents may be used to estimate the changes in insurance claims costs that may be expected by regulating the performance of buses in regards to the slip resistance of their flooring.

Initial and ongoing operational costs were assumed to be constant as the installation of different flooring was considered unlikely to cause any changes in operational practice, whilst cost differentials in environmental and infrastructure costs were not considered within the scope of this safety measure.

Table 8-6 and Table 8-7 present the costs associated with the new build and retrofit solution respectively.

Table 8-6: Estimated changes in costs per bus (NPV) and total fleet costs (NPV) over the 12-year analysis period (2019-2031) for the new build Non-Slip Flooring [NSF] safety measure solution (cost reductions in (parentheses))

Safety Measure Solution	Cost Description	Cost (NPV) per bus (£)	Total Cost (NPV) (£M)
NON-SLIP FLOORING	Change in Technology Costs	0	0
	Change in Implementation Costs	0	0
	Change in Operational Costs	0	0
	Change in Insurance Claims Costs	(2.1)-(0.3)	(0.022)-(0.003)
	Totals	**(2.1)-(0.3)**	**(0.022)-(0.003)**

Table 8-7 Estimated changes in costs per bus (NPV) and total fleet costs (NPV) over the 12-year analysis period (2019-2031) for the retrofit Non-Slip Flooring [NSF] safety measure solution (cost reductions in (parentheses))

Safety Measure Solution	Cost Description	Cost (NPV) per bus (£)	Total Cost (NPV) (£M)
	Change in Technology Costs	88-123	0.95-1.33

Safety Measure Solution	**Cost Description**	**Cost (NPV) per bus (£)**	**Total Cost (NPV) (£M)**
NON-SLIP FLOORING	Change in Implementation Costs	131-184	1.42-2.00
	Change in Operational Costs	0	0
	Change in Insurance Claims Costs	(3.06)-(0.43)	(0.033)-(0.005)
	Totals	**216-306**	**2.35-3.33**

8.7 Benefit-cost analysis outcomes

Table 8-8 provides estimates for the break-even costs, discounted payback period and benefit-cost ratios associated with specifying the performances for the NSF new build and retrofit solutions. For the new build solution the benefit-cost ratios is shown as ‘Return on Investment’ (RoI) to indicate that the new build solution will likely to provide operators with a return on their investment within the year it is implemented and continue to provide a RoI for all years within the analysis period. This is because a zero additional cost for implementation has been assumed. The break-even costs, however, show that if additional costs rise above £8.03 a benefit-cost ratio of less than 1 would result, i.e. the costs of implementation would be greater than the value of the benefits.

For the retrofit solution the BCR is much less than 1 indicating that the costs of this solution, far exceed the value of the benefits. This is a function of the limited number of casualties affected by the safety measure and the costs associated with the retro fitting option.

Table 8-8: 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 and retro fit Non-Slip Flooring [NSF] safety measure solutions

Safety Measure Solution	**Solution Type**	**Break-Even Costs (NPV) (£)**	**Discounted Payback Period**	**Benefit-Cost (NPV) Ratio**
NON-SLIP FLOORING	New Build	1.27-8.03	2019	**RoI**
	Retrofit	1.71-10.80	2031+	**0.006-0.050**

9 Conclusions and recommendations

This section summarises the work carried out relating to the Slip Protection aspect of the Occupant Friendly Interiors safety measure. A summary of the key findings from each section is presented below and recommendations based on these findings relevant to the BSS are made. The opportunities to further develop this work are also provided.

This research was completed in 2018. The detailed specification, assessment procedures and guidance notes have been incorporated into the Transport for London specification for buses, which is a continuously updated document to keep pace with the latest technological and research developments. This report is not the specification for a bus and should not be used as such. Bus operators, manufacturers, and their supply chain should consult with TfL for the specification.

9.1 Summary of findings

A summary of the finding in each section of this report are presented in the following sub-sections.

9.1.1 Review of literature

- Slips trips and falls usually occur when the friction between the surfacing material and shoe is inadequate.
- The presence of contaminants can greatly affect the amount of friction, and by extension the slip risk through the squeeze film effect.
- The number of casualties arising from wet slips trips and falls is reported to be 19 between 2014 and 2017.
- Numerous measurement techniques and characterisation standards are available globally.
- In the UK the PSRT is recognised by the HSE as the most appropriate device for the characterisation of the slip potential of pedestrian flooring materials.
- In the UK the characterisation of slip potential is standardised in the UKSRG guidelines (The UK Slip Resistance Group, 2016).
- Flooring materials are available meeting a PTV of 36 (the requirement for a low slip risk material as defined in the UKSRG guidelines (The UK Slip Resistance Group, 2016).
- 13 materials used for bus flooring, manufactured by 5 companies were identified.

9.1.2 Development of a test protocol

- The UKSRG guidelines can be used as a test protocol with the following exceptions:
    - The use of the roughness meter is omitted from the test methodology.

  - A temperature range of 5ºC to 40ºC to be observed when making measurements for the assessment of bus floor slip potential.
  - Measurement to be made in all three directions if possible and a single direction where space constraints dictate.
  - During one test sequence, repeat measurements are made until the range of five consecutive measurements is three units or less and the mean of these 5 measurements calculated as the average PTV.
  - The slip potential is characterised using the values stated in Table 5-2.

9.1.3 Full scale assessment of bus flooring materials

- MEC materials
  - The MEC materials performed well and in general provide levels of wet slip resistance in the low risk category.
  - On some of the materials assessed an initial period was observed where the performance of materials improved with footfall.
  - After this period of improvement, all of these surfaces showed a reduction in slip resistance with footfall.
  - The surfaces not demonstrating an initial period of improvement showed a continual decrease in performance.
- Grooved vinyl materials
  - The grooved vinyl materials were not able to achieve the same performance as the MEC materials or smooth vinyl materials.
  - The grooved vinyl materials provided levels of slip risk in the medium and high categories
- High friction tape / MEC
  - The combination of MEC and high friction tape materials performed well and provided the highest wet slip resistance values of all the materials assessed.
  - This combination of materials may provide a good solution for the provision of slip resistance in high risk or high traffic areas.
- Smooth vinyl materials
  - The smooth vinyl material performed similarly to the MEC materials on Bus A but displayed a clearly different performance to the MEC materials on Bus C.
  - The overall performance of this material is classified as good.
- The use of polishing or sanding techniques, or the use of high friction tape, to improve slip resistance performance should be investigated.

9.1.4 Laboratory assessment of bus flooring materials

- Use of abrasion techniques
  - The assessment demonstrated that the use of abrasion techniques has the ability to substantially increase the slip resistance properties of typical bus flooring materials.
  - However the assessment also showed that the amount of trafficking applied on the specimens wasn`t enough. Comparing PTV values after 2.300 footfall to full scale testing where floors were tested on average after 0.5 million footfall is difficult and long life behaviours of assessed materials cannot be estimated.
  - In most cases equivalent mean PTV after trafficking above 40 was observed, achieving the requirement for low slip risk when in service. However this was only observed in the cases where highly aggressive methods of abrasion were used.
- Use of high friction tape
  - The application of high friction tape produced the greatest increase in PTV observed, but the duration of this improvement was called into question as the tape was only viable for a limited amount of trafficking.
- Initial performance of bus flooring materials
  - Data collected during the laboratory assessments has shown that new materials have a PTV between 25-35. The UKSRG state that the PTV value for low slip resistance is equal or greater than 36. This suggests that it would not be possible for these materials to meet the minimum criteria for low slip resistance. It should be noted however that materials with a PTV of >36 PTV are commercially available. Primary evidence for this was collected following the laboratory assessments.

9.1.5 Cost-benefit analysis

- A return on investment (RoI) was calculated for the new build installation, because a zero cost for implementation was assumed.
- Benefit-cost ratios less than 1 were observed for the retro fit option.

9.2 Recommendations for the BSS

This section presents the recommendations for the BSS and discusses the basis of these recommendations from the work carried out.

9.2.1 Slip resistance should be measured using the techniques described in section 6

The review of literature showed that the PSRT is the skid resistance measurement tool of choice for the UK HSE and that the UKSRG guidelines also recommend its use. A detailed analysis of the UKSRG guidelines however highlighted some minor aspects that required adjustment to allow the guidelines to be applied to the bus scenario.

The full scale assessment of bus flooring materials exercise demonstrated that the derived technique is capable of characterising the skid resistance performance of a variety of bus flooring materials in situ. The laboratory testing demonstrated that the skid resistance characterisation of these materials is also possible under laboratory conditions. This allows for extra flexibility of assessment over techniques such as the ramp test which can only be conducted in the laboratory using large, specialist, equipment.

9.2.2 Materials should be replaced during standard servicing intervals

The CBA demonstrated that Benefit Cost Ratios (Burrs) less than 1 were calculated for the “retro-fit” condition, i.e. costs are greater than the value of benefits for the “new build” condition (which includes standard servicing intervals) however, a cost benefit was observed when defective materials are replaced. Based on these figures it is only cost effective to replace flooring materials during the standard servicing intervals when defective flooring would be replaced anyway.

9.2.3 Flooring materials should achieve a mean PTV of ≥36 at the point of entering service, and a mean PTV of ≥40 after 100,000 passengers have accessed the vehicle, or after an in-service period of 6 months, whichever is sooner

The UKSRG guidelines state that materials with an average PTV of greater than or equal to 36 can be characterised as having a low slip risk. However, this characterisation is heavily caveated and requires adjustment to account for the special conditions pertaining to buses. Exactly how much this value should be adjusted by is the topic of the discussion presented here.

<u>Initial slip resistance performance</u>

The full scale and laboratory assessment of bus flooring materials has shown that some flooring materials require a wearing-in process before they are able to achieve their full slip resistant capabilities. In consultation with material manufacturers it has become apparent that it is unlikely that some materials will be able to meet a PTV when new of greater than 36. However, given that this is the threshold for low slip risk as presented by the UKSRG it has been deemed prudent that this level should represent a minimum requirement for bus floorings. **It should therefore be specified that all materials should meet a requirement of 36 PTV from the point of entering service**.

However, it is also understood that special cases may occur whereby flooring materials provide a slip resistance of less than 36 PTV, but that this performance could prevail for a very short period of time. With this in mind the risk associated with these materials is also likely to be very low.

The CIRIA document C652 (Carpenter, Lazarus, & Perkins, 2006) presents the following slip probabilities based on different levels of PTV.

Table 9-1: PTV and slip risk

PTV	Slip risk
36	1 / 1,000,000
34	1 / 100,000
29	1 / 10,000
27	1 / 200
24	1 / 20

For the purposes of this task and in the absence of clarifying evidence it has been assumed that the slip risk represents the risk of any given person (subject to the caveats presented in the UKSRG guidelines) slipping. These figures can be used to calculate an acceptable exposure time to the public for materials that provide skid resistance levels below 36 PTV, this can be achieved using Equation 9-1:

$$n = \frac{Log(1 - P(y))}{Log(\frac{P(x) - 1}{P(x)})}$$

Where:

- n = the size of the population that can be exposed to a surfacing with slip risk P(x) before the probability of any given person in that population slipping exceeds P(y).
- P(y) = the probability of any given person in the exposed population slipping

P(x) = the slip risk associated with the flooring (

- Table 9-1).

Equation 9-1: Calculating an acceptable population size to be exposed to materials with less than 36 PTV

Using Equation 9-1, it can be calculated that exposing pedestrians to a surfacing with a PTV of 29, and allowing the risk of a single person within the exposed population slipping to equal 0.5 (50%) then the maximum population that should be exposed is 6931 people.

Using a rule of thumb that a bus on the TfL network will transport 200,000 people per year, the length of time of exposure (in weeks) would equal 6931 * 52 / 200,000 = 1.8 weeks.

At this time, without further evidence, it is thought unlikely that the slip resistance of the floor will increase from 29 to 36 in about two weeks and if it did it would likely be possible to pre-treat the floor to have a PTV of 36 before entry into service. Also to allow a further increase in slip risk is thought to be unacceptable. Therefore, on this basis it is recommended that no concessions are given to the recommendation that all materials should meet a requirement of 36 PTV from the point of entering service.

<u>In service slip resistance performance</u>

Because of the caveats applied to the low slip risk category, the in-service slip resistance of bus flooring materials should be greater than 36 PTV. Section 5 has presented a justification for increasing the low slip risk PTV threshold by 10 points to 46 PTV. However there are other considerations outlined below which should be meditated on in order to allow a practicable limit to be set:

- Potential measurement variability,

All measurement technologies are subject to measurement variability and the variability of a measurement technique is characterised by the reproducibility. The average reproducibility of the pendulum test with a 96 IHRD slider is reported in BS EN 13036-4 (British Standards Institution, 2011) as 2.4 PTV to a single standard deviation. This means that during any measurement exercise with the pendulum tester 68% of the measurements made should fall within 2.4 PTV of the mean.

The effect of this is that in order for the slip resistance of a surface to be measured at 46 PTV, it would potentially have to actually provide 48.4 PTV once measurement variability is taken into account.

- Manufacturing and design tolerances,

In a similar way that measurement technologies are all intrinsically variable, so too are manufacturing techniques. Manufacturers account for variabilities in the manufacturing process by working to tolerances. Discussions with bus flooring manufacturers has revealed that the skid resistance of bus flooring materials are typically designed with manufacturing tolerance of 3 PTV.

The effect of this, combined with that of the effect of measurement variability is that for a manufacturer to be confident that their material would achieve a slip resistance performance of 46 PTV, it would be designed to provide a slip resistance of 51 PTV.

To add context to this, materials are currently designed to provide a minimum PTV of approximately 36 PTV and the full scale testing has demonstrated that some materials are capable of providing slip resistance characteristics of 60 PTV. So if a material was designed to provide a minimum PTV of 46 it is possible that the actual in-service slip resistance could be as high as 70 PTV.

- Initial wearing-in period

Slip resistance assesments of floors on in-service buses found that for some of the MEC materials assessed an initial period was observed where the performance of materials improved. It is hypothesized that this was a result of the material wearing in response to footfall and/or aging which exposes more of the embedded material offering improved slip resistance performance. This effect is also common on some road surfacings where it is related to the wearing of bitumen from aggregate particles.

- Cleaning methodologies,

Flooring materials with very high levels of PTV can pose issues for maintenance procedures such as cleaning. Materials with high levels of slip resistance tend to possess a texture that has the effect of trapping dirt and contaminants that cannot be easily cleaned. Furthermore on surfaces with very high levels of slip resistance, specialist cleaning equipment can be required as the surfaces may damage traditional cleaning equipment due to their abrasive properties.

- User perception

Flooring materials with very high levels of slip resistance can also pose a potential hazard to users. This results from users anticipating a surface with a level of slip resistance much lower than that which is provided and placing their feet expecting a certain amount of slip in the surface. In some cases, when this very small amount of slip is not experienced it can cause users to become unstable adding a falling risk.

With all of these factors in mind, it is considered appropriate that after 100,000 passengers have accessed the vehicle, or after an in-service period of 6 months, whichever is sooner, the PTV of bus flooring materials should be at least 40 PTV.

This level balances the need to increase the low slip risk band as presented in section 5 with the considerations of manufacturers, measurement variability, initial wearing in period, maintenance and user perception.

9.2.4 The in-service PTV requirement should be continually challenged

It should be noted that the in service requirement of 40 PTV is substantially below that measured on some in-service buses which can be as high as 60 PTV. Furthermore, that the justification for increasing the PTV associated with various risk categories is sound and the level for low slip risk is 46 PTV. At the same time, it is recognised that the measurements made on in-service buses constitutes a relatively small amount of evidence, owing to the percentage of the TfL bus fleet assessed. With this in mind, the in-service requirement should be periodically reviewed based on further evidence collected from in-service buses, and with consultation with material manufacturers.

10 References

(n.d.). Retrieved from www.onaverage.co.uk: https://www.onaverage.co.uk/body-averages

ASTM International. (2011). *ASTM-D2047-2011 Standard Test Method for Static Coefficient of Friction of Poilish-Coated Flooring Surfaces as Measured by the James Machine*. Retrieved 2017, from https://www.document-center.com/standards/show/ASTM-D2047

ASTM International. (2013). *ASTM E303-93 Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*. Retrieved 2017, from https://www.astm.org/Standards/E303.htm

British Standards Institution. (2002). *BS 7976-2:2002 Pendulum testers - Part 2: Method of operation.* London: BSi.

British Standards Institution. (2011). *BS EN 13036-4. Road and airfield surface characteristics. Test methods. Method for measurement of slip/skid resistance of a surface. The pendulum test.* London: BSi.

Carpenter, J., Lazarus, D., & Perkins, C. (2006). *CIRIA C652 Safer surfaces to walk on - reducing the risk of slipping.* London: CIRIA.

Chang, W., Matz, S., Grönqvist, R., & Hirvonen, M. (2010). Linear regression models of floor surface parameters on friction between Neolite and quarry tiles. *Applied Ergonomics, 41*(1), 27-33.

Chang, W.R. (2002). The effects of slip criteria and time on friction measurements. *Safety Science, 40*(7-8), 593-611.

Chang, W.-R., Kim, I.-J., Manning, D. P., & Bunterngchit, Y. (2001). The role of surface roughness in the measurement of slipperiness. *Ergonomics, 44*, 1200-1216.

Chang, W.R; Matz, S. (2001). The slip resistance of common footwear materials measured with two slipmeters. *Applied Ergonomics, 32*(6), 549-558.

Chen, C., Chen, Z., Chang, C., & Lin, F. (2015). The Slip-resistance Effect Evaluation of Floor Roughness Under Different Liquid Viscosity. *Procedia Manufacturing, 3*, 5007-5013.

Chi-Yuang Ya, Hsin-Hung Tu. (2008, November). Foot surface area database and estimation formula. *Applied Ergonomics*, pp. 767-774.

D, S. P. (2018). *Specification for bus flooring-BSS, test report for non slipping surfaces.* Crowthorne: TRL ltd.

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

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

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

German National Standards. (1992). DIN 51097:1992 Testing of floor coverings; determination of the anti-slip properties; wet-loaded barefoot areas; walking method; ramp test .

German National Standards. (2004). DIN 51130:2004 Testing of floor coverings; determination of anti-slip properties; workrooms and fields of activities with slip danger; walking method; ramp test .

Health and Safety Executive. (2006). *The underlying causes of falls from vehicles associated with slip and trip hazards on steps and floors.* Norwich: Health and Safety Laboratory.

Health and Safety Executive. (2012, May). *Assessing the slip resistance of flooring. A technical information sheet*. Retrieved October 2017, from http://www.hse.gov.uk/pubns/geis2.pdf

Hosking, J. R., & Woodford, G. C. (1976). *LR738 Measurement of skidding resistance. Part II. Factors affecting the slipperiness of a road surface.* Crowthorne: TRL Ltd.

Kirk, A., Grant, R., & Bird, R. (2003). Passenger casualties in non-collision incidents on buses and coaches in Geat Britain. *18th International Technical Conference on the Enhanced Safety of Vehicles* (pp. 1-10). Nagoya: US Department of Transportation.

Lemon, P., & Griffiths, S. (1997). *Further application of squeeze film theory to pedestrian slipping.* Health and Safety Executive.

Lin, L. J., Chiou, F. T., & Cohen, H. H. (1995). Slip and fall accident prevention: A review of research, practice, and regulations. *Journal of Safety Research, 26*(4), 203-212.

Liu, L., Li, K. L., Chen, C., & Chen, C. (2010). Friction measurements on “anti-slip” floors under shoe sole, contamination, and inclination conditions. *Safety Science, 48*(10), 1321-1326.

Moore, D. (1972). *The friction and lubrication of elastomers, International series of monographs on material science and technology.* New York: Oxford Pergamon Press.

Nicholls, J. C. (1997). *Laboratory tests on high-friction surfaces for highways.* Crowthorne: TRL.

Proctor, T., & Coleman, V. (1988). Slipping and tripping accidents and falling accidents in Great Britain present and future. *Journal of Occupational Accidents, 9*, 268-285.

Standards Australia. (1999). HB197:1999 An Introductory Guide to the Slip Resistance of Pedestrian Surfaces.

Standards Australia. (2013). AS 4586 Slip Resistance Classification of New Pedestrian Surface Materials. Retrieved from https://infostore.saiglobal.com/preview/as/as4000/4500/4586-2013(%2ba1).pdf?sku=1636572

Standards Australia. (2013). AS 4663 Slip Resistance Measurement of Existing Pedestrian Surfaces.

Standards Australia. (2014). HB198:2014 Guide to the Specification and Testing of Slip Resistance of Pedestrian Surfaces. Retrieved from http://www.replas.com.au/wp-content/uploads/2015/05/Guide-to-the-specification-and-testing-of-slip-resistance-of-pedestrian-surfaces-2.pdf

The UK Slip Resistance Group. (2016). *The assessment of floor slip resistance - The UK slip resistance group guidelines.* UKSRG.

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

Transport for London. (2016). *Travel in London: Report 9.* London: Transport for London.

Transport for London. (2017, June). Bus safety data. *London bus safety dashboard*. London. Retrieved October 4th, 2017, from https://tfl.gov.uk/corporate/publications-and-reports/bus-safety-data#on-this-page-3

UK Slip Resistance Group. (2016). *The Assessment of Floor Slip Resistance. The UK Slip Resistance Group Guidelines Issue 5*.

11 Acknowledgements

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Appendix A General cost-benefit analysis approach

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

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

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

(Equation 2)

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 3)

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 4)

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 5)

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 6)

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 7)

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

The Transport for London Bus Safety Standard: Slip Protection

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

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

Slips on buses are also a cause of injury for bus passengers. There are well established methods of measuring the slip resistance of flooring, and these have been modified to suit buses. The test method involves using a pendulum device with a swinging shoe plate; the greater the resistance the less the shoe plate moves after it hits the floor. The BSS will require a minimum skid resistance of the anti-slip flooring fitted in the buses.

Other titles from this subject area

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

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