

An analysis of bus interior headroom for future design applications

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Abstract

This research investigated the contextual underpinning and longevity of Australian vehicle standards for route bus passenger headroom—standards developed around Internal Combustion Engine (ICE). With growing interest in Electric Vehicle (EV) technologies, Australian Design Rule (ADR) 58.6 Head Room was examined for passenger safety, comfort and relevance to potential future vehicle design.

Four bus interior configurations were modelled to visualise the applications of ADR 58.6. These configurations were then analysed by comparing them to anthropometric data to determine whether accommodation was appropriate. The results found that ADR 58.6 only assures sufficient passenger accommodation when applied in a rear engine, low-entry route bus. A second, qualitative, analysis compared the ceiling height of buses to other public transport vehicle interiors. Results of this comparison contribute an understanding of what may be culturally acceptable as a new standard.

Research discovered that current Australian route bus headroom standards only give a satisfactory result when applied to a specific ICE configuration. When designing for alternative ICE configurations or EV drive technologies, these standards may lead to potential problems for passenger safety and comfort. Findings highlight the need to revise ADR 58.6 ensuring relevance to advancements in technology and vehicle design. Recommendations are made to this effect.

1. Introduction

Australian route buses have shared a long-standing relationship with the Internal Combustion Engine (ICE). This paper examines the implications of such a relationship and its influence on vehicle standards for passenger accommodation.

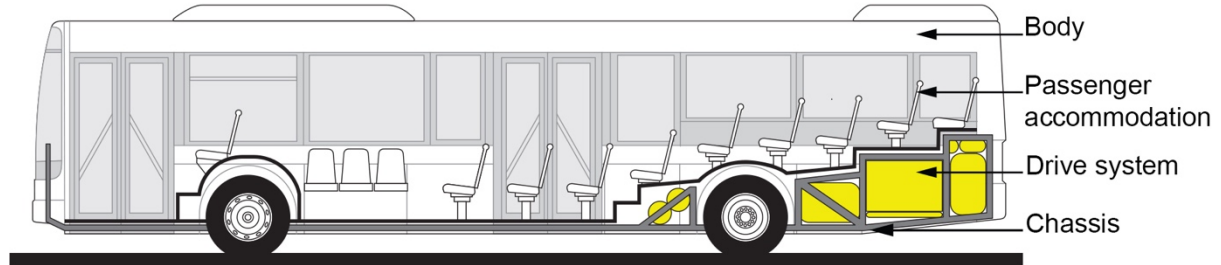
Route buses are a prominent public transport mode in Australian cities alongside trains and trams. They operate across urban and suburban areas transporting passengers on short and long commutes. Space within the vehicle is, therefore, allocated for both seating and standing passengers to travel in a safe and comfortable manner. Their design can be described in four key areas: the drive system, chassis, body and passenger accommodation (Figure 1). The drive system—most commonly an ICE—substantially influences chassis design as engine configuration and consequent forces govern structural arrangement. This creates a foundation for floor, framework and panels that form the vehicle body. Passenger accommodation is contained within the parameters of body configuration, highlighting its interdependence with other major areas.

Australian bus design is governed by a combination of federal acts, including Australian Design Rules (ADRs), Disability Standards for Accessible Public Transport (DSAPT), and Australian Standards (AS), as well as state and territory regulations established by local government, such as Perth's Public Transport Authority (PTA). In particular, ADR 58 sets out "Requirements for Omnibuses Designed for Hire and Reward" (Department of Infrastructure and Transport 2012 a). It outlines a number of minimum requirements for passenger

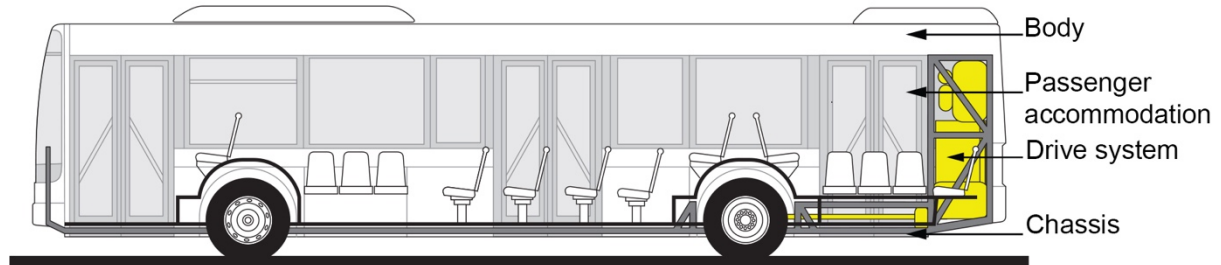
accommodation, including Section 58.6 that focuses specifically on headroom for standing passengers. This section states a minimum ceiling height of 1800mm for accessing seating along a longitudinal aisle (ibid).

Figure 1. Key areas of low-entry and low-floor route buses

Low-entry configuration



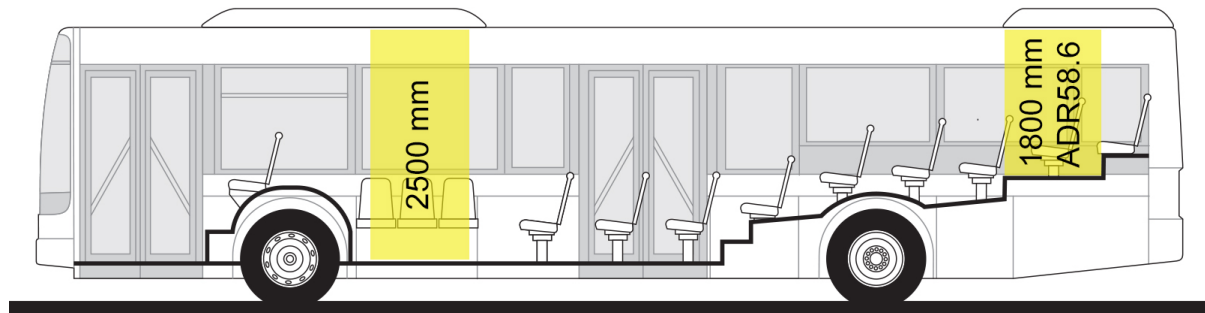
Low-floor configuration



A majority of route buses are designed in one of two common configurations: low-entry or low-floor shown in Figure 1. In these configurations the engine and related components are located behind the rear axle, underneath a raised floor or within a vertical column. Respectively, the former accommodates maximum seating and low-entry, while the latter allows for a stepless centre aisle throughout the low-floor vehicle as well as a third entry door behind the rear axle. The low-floor configuration is common in Europe where greater standing passenger capacity is required to accommodate higher passenger numbers. Australian operators, on the other hand, commonly specify the low-entry configuration to achieve maximum seating capacity. In this configuration, drivetrain components are housed at the vehicle rear in the engine bay to improve maintenance access and reduce drivetrain complexity. Floor level above this area is raised, requiring the vehicle interior to be designed with a stepped floor. National head clearance regulation ADR 58.6 is then applied to a small portion of the interior that contains seating above this raised floor. Buses are commonly constructed with straight material sections; thus, roof height throughout the rest of a low-entry vehicle increases gradually toward the front as shown in Figure 2. Low-floor buses don't share this characteristic and can be designed with continuous headroom of 1800 mm, significantly reducing total vehicle height. Lower buses require less construction material, have lower vehicle mass and reduce impact profile for over hanging street signs and branches. These factors may seem desirable, though cannot be prioritised ahead of safe and comfortable passenger accommodation.

Figure 2. Headroom standard application on low-entry bus

Low-entry configuration



As Australia's population increases (Australian Bureau of Statistics 2013), state governments attempt to encourage public transport use over the car to cope with growing transportation demands (for example, State Government of Victoria, 2014). With growing public transport use, Australian operators may soon move away from low-entry buses with maximum seating and favour low-floor configurations for their superior accommodation of standing passengers.

Alongside accommodating a growing population, petroleum powered vehicles present further concerns over fuel supply longevity (Moriarty & Honnery 2011) and adverse environmental impacts, such as air pollution (Department of Infrastructure and Transport 2012 b). Electric Vehicle (EV) buses are seen to alleviate these concerns by producing zero local emissions during operation and reducing fossil fuel dependence, allowing a transition to renewable energy sources (Kuhne 2010). Further to these benefits, the International Association of Public Transport (UITP) has also expressed interest in EV buses for their potential to enhance vehicle design and improve passenger experience. Improved accessibility is suggested through "purpose-designed" low-floor boarding at all doors (International Association of Public Transport 2012). If applied, accessibility may be improved for passengers in a wheel chair or with a stroller. Ingress and egress may also be improved through larger unobstructed standing areas at each door. Current low-floor buses also allow this design feature; however, EV buses are seen by the UITP to increase low-floor area within the vehicle and improve interior layout flexibility beyond that of ICE counterparts. A prominent drawback of EV buses is their limited capacity for energy storage and subsequent range restrictions. Incorporating larger on-board batteries is one way to address this issue. Some EV bus manufacturers attempt this by locating battery packs on the vehicle's roof, where they present no intrusion to passenger accommodation. This does, however, increase the overall vehicle height and impact profile, raising the risk of collision with street signs and tree branches. A lower interior ceiling height may allow incorporation of large roof-mounted battery packs without significant increase to the total vehicle height. Though this, once again, must not come at the cost of safe and comfortable passenger accommodation.

With traction technologies advancing and passenger capacity challenges to our public transport service, it is important to analyse the applicability of current standards to future design solutions. If greater standing room becomes a priority, or EVs gain prevalence in the Australian market then ADR58.6 requires review before application to future bus designs.

2. Passenger comfort

Although the notion of comfort may be familiar, it is also somewhat difficult to define and measure. This research is dealing with only one element of the human-machine interface—headroom—and yet this touches both basic compliance and comfort topics.

The primary objective of ADR58.6 is whether a human will fit in the vehicle. As such, the height deals with accommodation of the tallest passengers, all others may fit. The classic human factors conundrum of where to exclude some humans, or design a vehicle with headroom accommodating all humans will not be discussed here, beyond the notion that as public transport the vehicle ought to exclude nobody. This section intends to raise elements of ceiling height pertaining to comfort, beyond basic fit.

Beyond the basic fit, how then is comfort affected by ceiling height? Comfort comes to the fore in creating a vehicle that may be considered pleasant to ride in. A precise definition of comfort is elusive, but two useful definitions are the absence of discomfort (Oborne 1978) or when a person has no awareness of their environment (Branton 1969). In trying to achieve these ends, we consider how the specification of ceiling height may affect the overall feeling of comfort. Referring to previous work towards a taxonomy of passenger comfort (Napper et al. 2015) we find that ceiling height impacts dynamic riding comfort, physical safety, transport information, social safety, and task activation.

Dynamic riding comfort is affected through standing accommodation, as passengers can expect to undertake a journey without a seat, especially in peak periods. Since the bus vehicle is a dynamic body acted on by a variety of forces, an amount of clearance from a passenger's head to the closest hard surface is necessary. This dynamic experience is related to physical safety from harm.

Ceiling height specification has an important corollary in affecting window size. The following three points are discussed with relation to this. Transport information forms part of the comfort milieu when considering the cognitive task of navigating a transport system and through it, an environment. The "organisational comfort" (Mayr 1959) of a system is in part determined by access to information. Windows allow passengers to determine position along a route, view stop names, traffic conditions and anticipate turns (International Association of Public Transport 2006). A view of the surrounding environment also helps to prevent passenger motion sickness while the vehicle is travelling (Golding 2006). As a result, window size and its relative position to the human eye must be considered through the balance of passenger experience.

The impact of ceiling height, and knock-on effects that this has on views in and out of windows also relates to the social safety element of comfort. Large windows are suggested to create a safe environment and desirable travel experience (International Association of Public Transport 2006; Transport Research Laboratory 2004). The vehicle should have a clear view visual connection to the outside world, in order to maintain surveillance of public space. A ceiling height that is too low will interfere with such a view, while as observed in the current bus fleet, the somewhat unnecessary window height at the front of a low-entry vehicle do not create any detrimental outcomes.

Finally, in relation to window height, the activation of the travel experience, and indeed one fundamental pleasant utility afforded transit riders is the ability to gaze out the window. A structured observational study performed by Russell et al. (2011) reported that 65% of passengers were found to be "looking ahead" or "out the window" during bus travel. Bronkhorst & Krause (2004) support this finding, listing "staring out the window" as one of the three most popular activities for passengers on public transport, reinforcing the importance of windows from a passenger perspective. The authors also note that window staring behaviour can be a useful means to alleviate some of the detrimental impacts of close proximity to strangers. Whether this is an active task of observation or passive one of amusement, the creation of a ceiling height standard would do well to accommodate this amenity.

3. Quantitative analysis

Anthropometric data was referenced to understand standing passenger characteristics and requirements. This data informed a quantitative analysis of current headroom and potential headroom standards for route buses. As window visibility is an important consideration, eye level data was also considered to analyse visibility for standing passengers.

Table 1. Adult anthropometric stature data

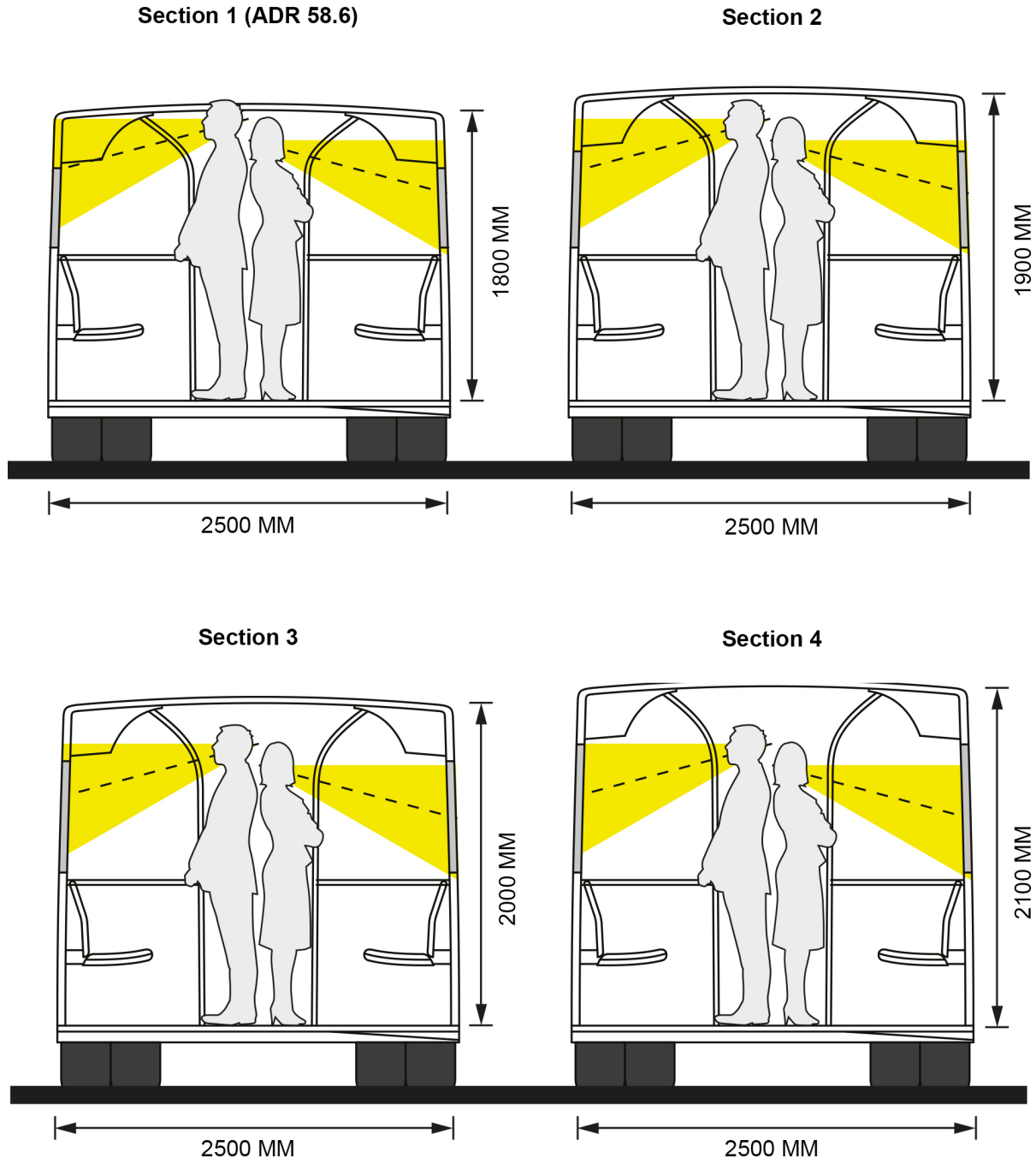
	Passenger stature (mm)				Passenger eye height (mm)			
	Female 50 th %tile	Male 50 th %tile	Female 95 th %tile	Male 95 th %tile	Female 50 th %tile	Male 50 th %tile	Female 95 th %tile	Male 95 th %tile
Great Britain (Pheasant)	1610	1740	1710	1855	1505	1630	1610	1745
North America (Pheasant)	1625	1755	1730	1870	1519	1644	1622	1759
Australia (Ward)	-	-	1730	1875	-	-	-	-

Pheasant (1988), lists average stature and eye heights for adults in North America and Great Britain. From this data it is evident that North Americans are on average slightly taller than the British—refer to Table 1 for anthropometric data. In a study of Australian university students, Ward (2011) found similar results for the 95th percentile stature. Though the Australian data is partial, it would be reasonable to expect a comparable average eye height to those presented for North America.

The method of virtual prototyping was applied to represent anthropometric data within a bus interior. Virtual evaluation tools are commonly used to minimise investment into physical prototypes during early stages of a design process (Kulkarni et al. 2011). Based on anthropometric data, basic volumes were drawn up using Computer Aided Design (CAD) software Autodesk Alias Automotive to represent standing passengers. Only data for the 95th percentile female and male passenger was incorporated into the drawings as headroom and window visibility would have greatest impact at the upper end of the data set. The information was used to determine the uppermost edge of the window and thus passengers of shorter stature would be accommodated.

Four low-floor interior sections were then generated using the aforementioned CAD software. Air duct profiles and window heights in these sections were based on dimensions provided by Volgren Australia for their Optimus low-entry route bus. Sections began with a floor to ceiling height of 1800 mm referenced from current standard ADR 58.6 (Department of Infrastructure and Transport 2012 a) and increased by increments of 100 mm up to a ceiling height of 2100 mm. Passenger volumes were then positioned inside these interior sections to represent someone standing in the aisle. Resting line of sight was considered to be 15 degrees, with an acceptable display zone of 0 – 30 degrees below the horizontal line of sight at eye height (Pheasant 1988). This allowed evaluation of window visibility for standing passengers.

Figure 3. Illustration of route bus interior sections for headroom analysis



- Preferred display zone *
- Window
- Resting eye level *
- 95 %ile Male & Female passenger *
- * Pheasant

As illustrated in Figure 3, Section 1—which was based on current headroom standards—was unable to accommodate standing male 95th percentile passengers. Standing female passengers were accommodated, though only just, with a head clearance of 70 mm. Both male and female passengers were able to stand in Section 2; however, head clearance for the male passenger was a mere 25 mm and window visibility was obstructed for both passengers by the vehicle's air ducts. Section 3 provided greater headroom for both and improved window visibility for the standing female passenger, making it possible for them to

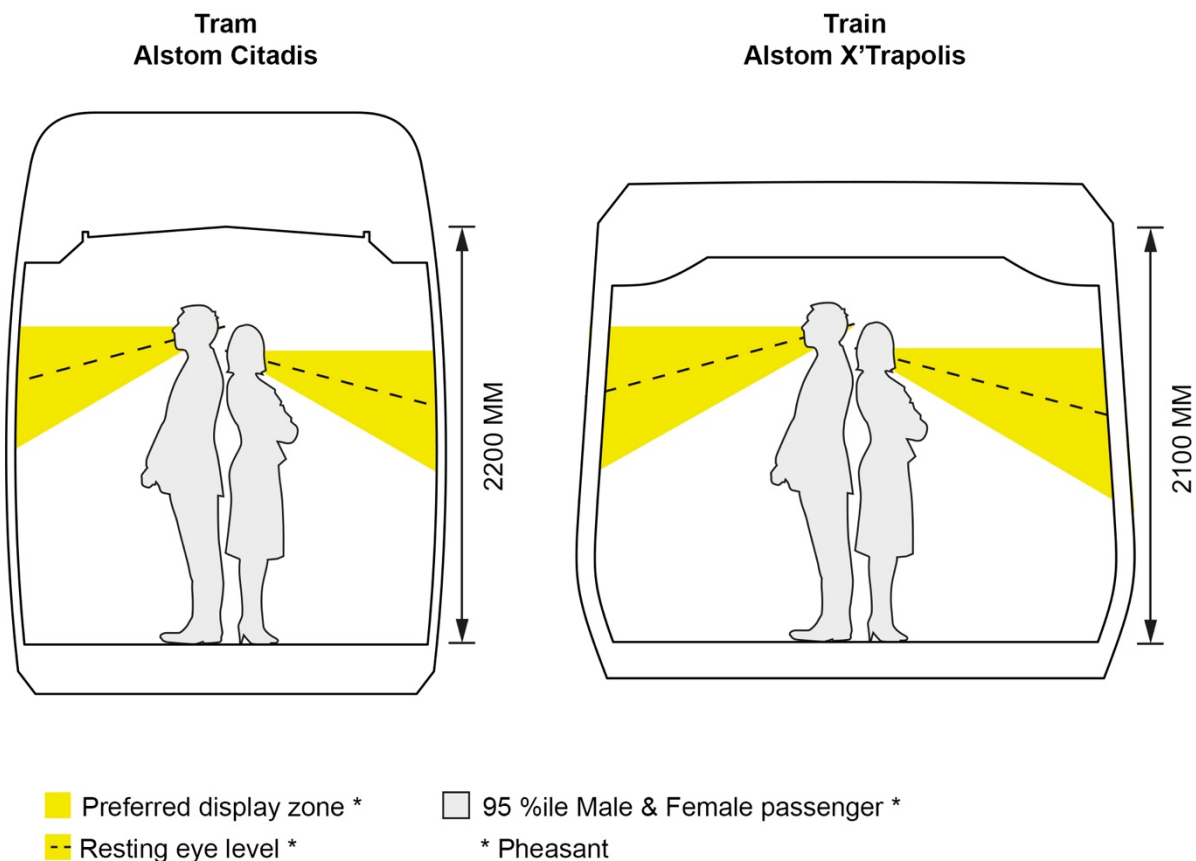
observe their surrounding environment during travel. Section 4 showed best results out of the four sections, accommodating stature and allowing window visibility for both male and female passengers.

Further to analysis results, it was noted that although Section 3 accommodated both female and male stature, it left little room for movement above the passengers' heads. Bus interiors are a dynamic environment, often travelling over uneven surfaces or speed bumps that cause occupants to move inside the vehicle. As such, passenger comfort required further consideration beyond that of a static numerical assessment.

4. Qualitative analysis

Interior concepts developed in the quantitative analysis were then compared against examples of existing low-floor public transport to inform a qualitative analysis of bus headroom standards. Trains and trams provide examples of existing low-floor public transport in Australia. Both accommodate a combination of standing and seated passengers within the vehicle and were referenced to gain a perspective of appropriate headroom for dynamic interiors.

Figure 4. Train and tram headroom examples



Interior sections for Alstom's X'Trapolis train (Alstom 2013) and Citadis tram (Alstom 2014) are illustrated in Figure 4. These exhibited largely similar spatial qualities to the low-floor bus interiors proposed in the previous section. Floor to ceiling measurements were taken along the centre aisle inside both vehicles showing dimensions of 2100 – 2200 mm for the tram and 2100 mm for the train. When compared to proposed bus interiors, these dimensions corroborated quantitative analysis results, suggesting that a 2100 mm ceiling height provides sufficient headroom for standing passengers in a dynamic interior.

Trams and trains are both popular public transport modes, transporting numerous passengers on a daily basis. This suggests an existing cultural acceptance of tram and train

interiors amongst patrons of Australian public transport. This is especially evident in cities like Melbourne where trams operate in the city centre frequently transporting large numbers of standing passengers on short commutes. If future buses required a low-floor interior to accommodate greater standing passenger capacity, then it may be assumed that passengers would adapt quickly to transport interiors that reference existing modes.

Some difference may nevertheless exist between buses, trains and trams due to vehicle construction and climate control requirements. These differences may reduce window visibility or standing passenger comfort; thus, it was considered important to further explore the spatial qualities of the forth interior concept—Figure 3, Section 4.

Figure 5. Full-scale interior test rig

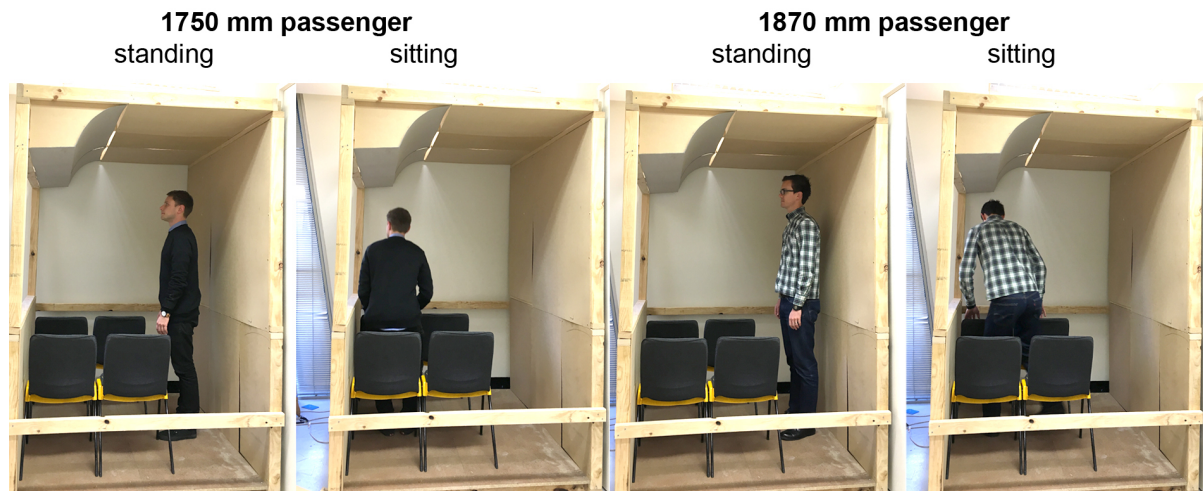


Figure 5 shows a full-scale test rig that was constructed to provide spatial understanding of the interior proposed in Figure 3, Section 4 from a passenger perspective. Created from wooden beams and panels, it included details of floor, ceiling, walls, air ducts and windows to simulate a bus interior. Physical “mock-ups” are considered essential to understanding spatial qualities in a design process (Dreyfuss 2003). The goal of this rig was to observe implications of ceiling height on passenger accommodation with reference to external vistas. The authors’ statures were measured at 1750 and 1870 mm, which correspond within the 95th percentile female and male range respectively (Pheasant 1988). When inside the test rig, both stood comfortably upright in the centre aisle with unobstructed window visibility. The interior provided comfortable views of the surrounding environment and allowed access to seating without intrusion of air ducts. This preliminary assessment showed promising signs of successful passenger accommodation on a low-floor bus; however, it was recognised that further testing with a greater participant sample size is still required to understand how it would perform when laden with passengers. Exterior information, such as stop and street signs should also be included at their correct height in further testing to assess how easily passengers are able to navigate during their journey.

5. Discussion

It is clear that existing design standards for passenger headroom were developed alongside low-entry ICE buses that preference maximum seating over standing capacity. Implementation of low-floor buses is possible in the Australian market and may be necessary in the future to accommodate growing bus ridership. It is, however, unconsidered by current design standards. Results from this study confirmed this, highlighting that the current headroom standard of 1800 mm (Department of Infrastructure and Transport 2012 a) was insufficient for accommodating standing passengers when applied to a low-floor route bus configuration. From the explored concepts, Section 4 presented a floor to ceiling height of 2100 mm, providing adequate passenger head clearance and a pleasant spatial

envelope. As shown in Figure 5, subjects were able to stand upright throughout the centre aisle and have full window visibility.

This study provided an initial evaluation of standing passenger comfort with regards to headroom. Though the quantitative data suggested sufficient headroom provision, further assessment is still required to better understand qualitative implications from such a decision. Passengers may experience different responses to ceiling height in situations of crowding or during turbulent travel, both of which are possible when travelling on a bus. Window vistas need further examination to ensure that passengers are able to see stop and street signs easily and at their correct height without having to adjust their standing positions. This is especially important for first time commuters that may be unfamiliar with a specific bus route and rely on external signage to navigate their journey.

Developing purpose-designed low-floor buses would allow an overall height reduction when compared to low-entry buses with a raised rear floor level. These new vehicles can achieve numerous enhancements as long as passenger headroom standards are maintained. Vehicle performance may be improved through a lower centre of gravity and reduced vehicle mass—both by-products of low-floor interiors. The vehicle's impact profile would also become smaller, reducing the potential for collision with tree branches and street signs. This is of particular importance for EV buses as it would allow extra space for battery storage on top of the roof without drastically increasing total vehicle height.

Passenger accommodation and comfort can be enhanced during peak operation through greater low-floor area throughout the vehicle. This may also reduce dwell time by improving ingress and egress as the challenge of a stepped floor level would be removed for disembarking passengers. These enhancements are desirable for passengers and operators alike, though they are difficult to regulate without suitable guidance for passenger comfort. This study showed that a lower overall vehicle height could be achieved safely by increasing the national standard for minimum headroom. Until updated, current ADR headroom standards are a potential barrier to advances in vehicle design and the transition away from oil-based ICE bus configurations.

6. Conclusion

This research examined future design applications of ADR58.6 that governs bus headroom. Through quantitative and qualitative assessment, it was determined that current standards only provided satisfactory outcomes for passengers when applied in a low-entry bus design—currently the most common design in the Australian market. When applied to a low-floor interior, a compliant design could result in unsuitable, uncomfortable or dangerous accommodation of standing passengers.

If Australian public transport patronage continues to grow and interest in EVs increases, vehicles with greater standing passenger capacity may eventually become commonplace in Australia. Standards must be updated to ensure that future vehicles are designed with adequate headroom in all potential configurations, including low-floor ICE and EV route buses. When developing a new headroom standard, it is important to reference other forms of low-floor public transport for existing, culturally accepted solutions.

The headroom standards proposed in this paper are an indication of what can be applied to accommodate standing passengers on low-floor buses. They are, however, an initial assessment, requiring further refinement and greater analysis before broad market application. Once developed, headroom standards may translate to other countries that have similar passenger and transport characteristics to those exhibited in Australia.

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