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An examination of three approaches to metro rolling stock design to ameliorate extended dwell times due to passenger growth and associated crowding.

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Abstract

Increased patronage of suburban rail in many cities of the world has effected network performance. Crowding, especially during peak travel times detrimentally effects dwell times thus reducing network capacity. This paper examines three approaches undertaken by three rail operators to the design of rolling stock in order to ameliorate this problem.

Each of the network operations examined in this paper were selected due to their different approaches to the problem but reflecting their own set of circumstances. Stockholm Lokaltrafik AB ran experimental carriages amongst its regular system to determine a new interior carriage design. The Melbourne suburban rail system explored expanding the door vestibule area. The third example, Rio de Janeiro's Metro, considered both the train interior and platform geometry to reduce dwell times.

The research reveals that in each case there is a great deal of pressure to remove seating from the carriage, a policy that often contradicts passenger perceptions of comfort. The purpose of this examination is to inform the design of new rolling stock interiors for future research.

1. Introduction

1.1 The problem

Rail is an important contributor to the movement of people and goods in many of the world's large cities. Suburban, metro and subway systems are very efficient in terms of the number of people moved relative to land use. Rail is a popular means of transport and becoming more so as urban populations increase. In the latter part of the 19th century when the London Underground opened (the first in the world) only 10% of the world's population lived in cities. Now in the early 21st century over 50% of the world's population live in a city (Burdett, Sudjec et al 2007). In terms of transit use, 80% of the population of Tokyo uses the subway, making some 2930 million-passenger journeys (Ibid 2009 figure) per year, the highest level of patronage anywhere in the world.

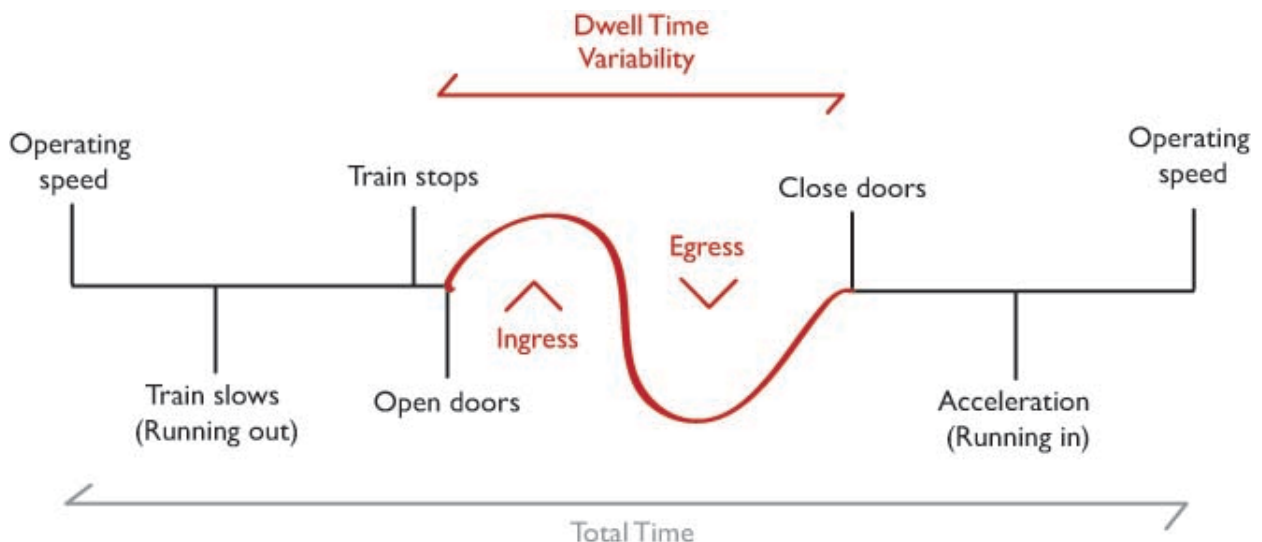
The growth in city populations has fueled increased rail patronage with the consequence that many train networks can struggle to be punctual. The most significant variable in the journey of a train is the time it will take paused at each station. This 'dwell' time is at the mercy of how long it takes passengers to board, alight and disperse within the train carriage or across the platform. At peak periods dwell times can become extended as passengers jostle to board or alight. It is general practice that timetables have built in 'recovery' time and attempt

to predict extensions of dwell time during peak periods. However with increased patronage the predictability of dwell times becomes more difficult. Delayed trains create a number of implications beyond poor punctuality including the extension of headways (the time gap between services). This extension is especially onerous if the lines are shared with express services and freight trains. Extended dwell times reduce network capacity leading to less services and more late services, ultimately impacting upon an operator's revenue and contributing to poor passenger perceptions of the mode.

Dwell time predictability is important in the creation of service timetables. To this end operators subdivide the dwell time to better understand where problems lie. Current timetable orthodoxy determines dwell times by mathematical means. While there are variations to the formula, they all in essence treat boarding and alighting as a linear period of time multiplied by a coefficient representative of how much passengers have been slowed down by other passengers, width of the doors and if they are carrying belongings. Accurate calculation of these dwell times will inform operators of the predicted capacity of the network and so drive timetables with some accuracy.

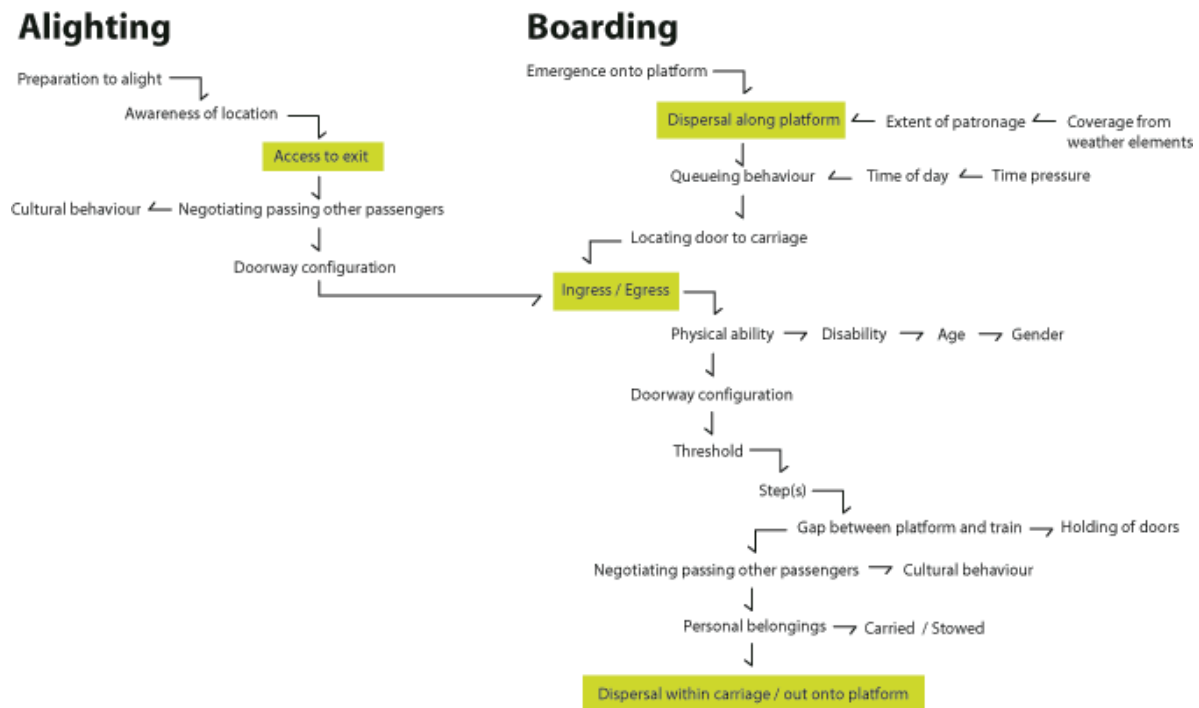
However while building mathematical models might simplify determining dwell times they also mask the intricate composition of the causes of extended stops. Studies show (Daamen et al 2008) that there is a wide range of qualitative variables that impact upon passenger behaviour while boarding and alighting. These factors include the prevailing culture of the passengers, their age, relative athleticism, the gap between the platform and the train, the level of the occlusion at the door and their motivations once within the train to finding a seat. These human factor variables are difficult to determine quantitatively, but they do relate strongly to the interface between the passenger and carriage. Figure 1, below, shows the points between predictable timing with where the unpredictable variation in dwell is located. Figure 2 (overleaf) encapsulates, as a flow chart, each of the 'factors' that effect the efficacy of the passenger to board or alight from a train and by implication impact upon the dwell time variability of the service.

Figure 1: Predictable and unpredictable components of dwell time. Authors' diagram



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Figure 2: Qualitative variables in alighting boarding. Authors' diagram



Extended dwell times imply difficulty in passenger boarding and alighting at anyone or more of the stages outlined in Figure 2 above. With significant increases in patronage, particularly during peak time, crowding itself is the significant determinant of extended dwell times. While passengers may not be particularly aware of the wider implications of delays at the station during boarding and alighting, crowding has a greater impact upon the overall perception of a comfortable journey.

Where passengers move to if they cannot get a seat is an internal layout problem. Passengers will stand where they can feel comfortable. Access to a grab rail or pole to stabilize their balance is one motivation but also the avoidance of entrapment with clear access to the door is another. This combination of factors frequently causes passengers to congregate in the door vestibules and occlude the doorway further compounding boarding and alighting problems.

Passengers caught in the middle of the vestibule area may have no accessible handholds and can fall into other passengers as the train moves. This deters an even dispersal within the train. Patrons who have managed to find a handhold are reluctant to move down the train to create space for others. In hot conditions, discomfort can escalate into psychological stress and even fainting.

1.2 The general parameters of comfort

Comfort is influenced by many factors in the environment and is a subjective phenomenon (Vink 2009). However the broad categories described by comfort researchers indicates that comfort can be divided into: -

- Thermal comfort.
- Acoustic comfort.

- Visual comfort.
- Physical comfort.

Placing patrons within a finite space prone to vibration and jolts makes addressing physical comfort a primary concern. On-board a crowded train passengers have restricted leg space, reduced movement, and discomfort due to vibrations and shocks (Goossens et al in Vink 2002). Add to this a passengers prior experience and mood. It is claimed that emotional feelings and mood play a role in the way someone evaluates a product or experience (Picard 1997). The perception of a comfortable journey will also be influenced by what they have been doing earlier in the day before catching the train (Ibid).

The motion of the train creates a level of instability for the standing passenger. Patrons are compelled to steady themselves by holding onto a rail or lowering their centre of gravity by sitting down and in some cases both. Standing journeys of less than 20 minutes can be tolerated in strong healthy people. However as journey length progresses so does fatigue upon the legs. If passengers are carrying belongings this is amplified. Fatigue leads to biomechanical pain, circulation discomfort, and restlessness (Zhang et al 1996).

The value that passengers place upon comfort can be measured. In a stated preference experiment carried out in Paris (Kroes et al 2006) the value of passenger comfort was a key variable. Patrons' response to 'not having a seat' was the equivalent of an additional 5 to 14 minutes of travel time, this penalty increasing with the length of the journey. 'Standing in a crowded train' was the equivalent to an increase of 27 minutes of 'disutility'.

Observations from a British stated preference survey highlighted overcrowding as a phenomenon that occurs more regularly than unreliability or poor frequency (Baker, Myers and Murphy 2007). Over-crowding in this study came down to simply 'not having a seat'. There are two pertinent repercussions to this study; passengers place value upon punctuality and general comfort on board the train. Yet the more passengers using the train the harder either of these aspirations are to meet. The discomfort caused by not having a seat is increased by the fatigue caused by standing and the potential anxiety at accessing a door to alight from. Given that these circumstances are not unique to one particular system in the world the authors' investigated three approaches to interior carriage design by different Transport Operating Companies (TOC's). Each one was chosen because of the variation in approach and the currency of analysis and solution.

2.0 Observations of other networks

The networks examined in this paper are: -

- Stockholm's Lokaltrafik, because they had built experimental carriages and ran them alongside their regular carriages.
- Melbourne network, because they had undergone modifications to some of their existing fleet to improve dwell time reliability.
- Rio Metro, because as one of the world's youngest systems they had the benefit of building in passenger flow measures that included the platform as well as the train.

2.1 Changing the design of carriage – the Stockholm experience

Storstockholm's Lokaltrafik AB, (Greater Stockholm Local Transit Company), commonly referred to as SL, is the TOC for all of the land based public transport systems in Stockholm. In 2008 SL embarked upon an investigation into alternative carriage interior design as a response to increased crowding, the effect of this upon punctuality and seeking an improvement in customer satisfaction. The anticipated data from the outcomes of the experiment was to inform a specification for new trains and the refurbishment of existing stock.

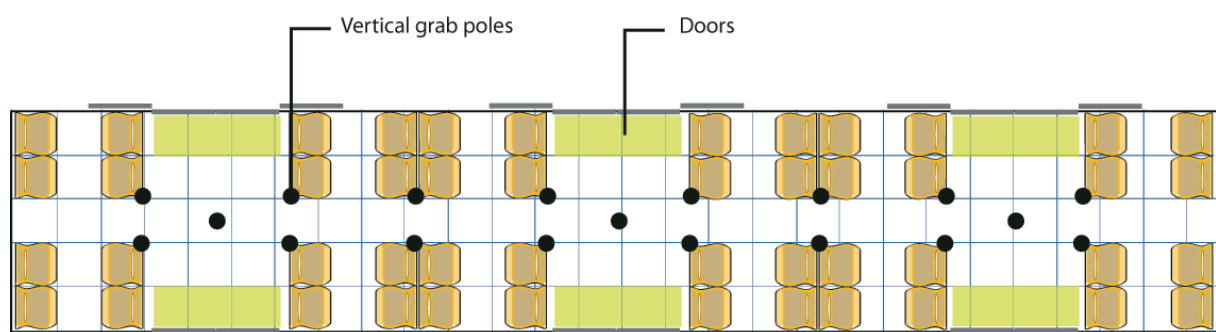
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Figure 3: Stockholm SL network



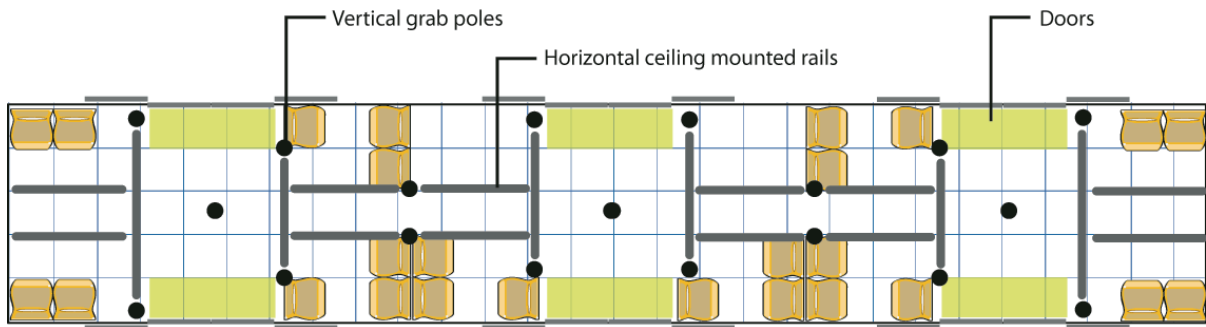
SL has two types of rolling stock, the C20 and the CX. The latter actually refers to a sub series of older carriages. For the purposes of their experiment the CX trains were used and then only one carriage located at the back of the set. SL runs eight car sets. The existing CX seating arrangement consists of transverse clusters of two seats abreast with a central corridor linking 3 door vestibules (Figure 4). The carriages contained 48 seats.

Figure 4. The interior arrangement of existing Stockholm rolling stock. Authors' diagram



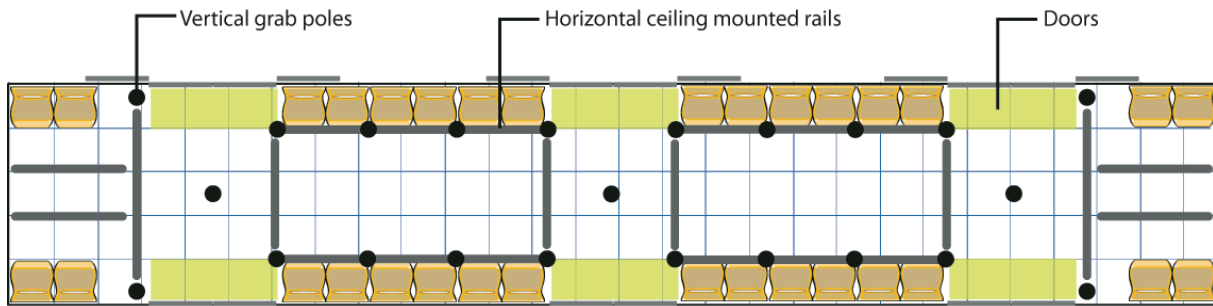
The process of re-designing the interior layout appears to be largely predicated upon increasing capacity for standing. Equally since existing rolling stock was to be used limitations were placed upon the engineers in terms of locating handrails and fixing points by the existing mechanical structure of the carriage. However two prevailing philosophies are embedded within the rationale of the experimental carriages. The first design continues with a transverse arrangement but removes 22 seats from the carriage, leaving a 26 seat car. Eight of these seats are folding, a feature not present in the original design.

Figure 5: Type 1 experimental interior with 26 seats. Authors' diagram.



The second carriage interior adopted a longitudinal arrangement of seats the full length of the carriage. This arrangement created a capacity for 32 seats, 24 fixed and 8 folding. The interior was entirely symmetrical. Two of the seat units are fitted with an armrest.

Figure 6: Type 2 experimental interior with 32 seats. Authors' diagram



Both designs had the following features in common: -

- No changes to doors or window positions.
- Refurbish interior with a modern scheme.
- 1.5m turning circle for wheelchairs and baby carriages.
- Contrasting colours for the visually impaired.
- Marked seats for the disabled.
- A common flexible area positioned by first door.
- Stanchions floor to ceiling.
- Stanchions located with respect to passenger flow.
- Reduction of holding places nearest the door.
- Wider aisles.

These carriages were introduced into the red line of the network for an eight-week period. They were placed within a set of regular normal arrangement carriages in a eight car set in the following way: -

1. Type 1 as the last two carriages of the set.
2. Type 2 as the last two carriages of the set.
3. Type 1 at the back and type 2 at the front of the same set.

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During the period that the trains ran SL conducted two methods of retrieving data. One a qualitative method through the running of focus groups and the second a questionnaire administered on board the train. The focus groups were subdivided into two. One with children (9-14 that travel without an adult) and the other with adults. Within the adult focus group the number of respondents was kept to 5 or 6. They were also split into groups by age and at what time of the day they normally used the train, i.e. rush hour and non rush hour. For the on-board questionnaire twenty questions were asked of a total of six hundred respondents over the eight-week period. Counting measurements were also taken by observers at stations of the trains pulling into the station, their dwell times recorded and how the number of passengers were distributed within the carriage.

2.2 Conclusions to the Stockholm experiment

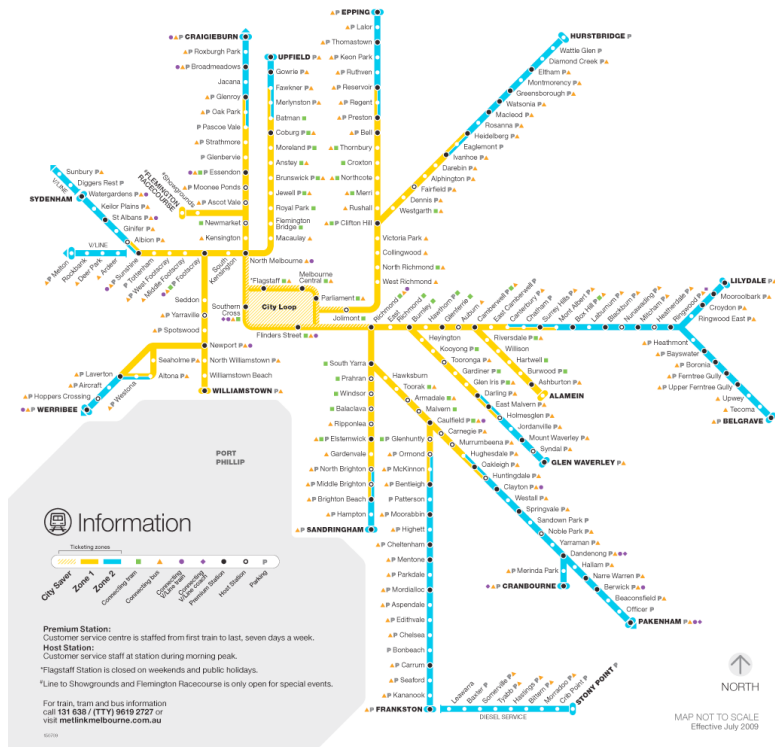
The collation of the data revealed that more than 90% of the respondents felt the punctuality was important or very important. 75% set higher priority to arriving on time over having a seat. Having a seat becomes more important than arriving on time when trips are over twenty minutes. Those travelling in rush hour are most satisfied with the test cars. The advantages with Type 1 are appreciated most by disabled persons. Those travelling during non-rush hour don't like the test cars; sitting is very important to them. Some respondents reported that they would have liked the experimental cars to be identified and that in both type 1 and 2 there were too few locations to hold onto. It was also reported that the banging of folding chairs was a noise disturbance.

From the perspective of the quantitative analysis there was 2-4 seconds reduction in dwell time for both interiors, with type 2 (longitudinal seating) being slightly quicker. Along the whole orange line Fruagen to Morby 20 to 45 seconds saving can be achieved (see Figure 3). Small time gains from shorter station stops can contribute to better compliance with the timetable, but doesn't solve all problems. Position of the test car in the train is important; first or last car in the set. Passengers emerge onto the platform from different station access points. Therefore late arriving passengers dash to the nearest carriage to the platform entrance from which they have emerged.

3. Removing seating from the door vestibule – Melbourne.

Melbourne is Australia's second largest city with a population of about four million. It has been experiencing rapid population growth over the last decade. From 2004 to 2010 the French TOC Connex held the franchise for Melbourne's suburban train network. Melbourne has 15 lines, 830Kms of track and 212 stations. The train fleet consists of approximately 357 three-car sets or close to 179 full length six-carriage trains. The Melbourne network carries 680,000 passengers each weekday (Victoria Department of Transport website, accessed 23/10/2010). Figure 11 shows the network as it stands in 2011.

Figure 6: Melbourne Metro network



Melbourne has five different types of rolling stock with differing door positions and seating arrangements. The track is broad gauge (1600mm) therefore affording a wide internal layout that can accommodate a 3 + 2 transverse seating layout. However just under half the rolling stock runs a 2+2 transverse seating arrangement, including all the newer carriages. All trains carry some longitudinal seating adjacent to end vestibules.

The nature of the Melbourne network dictates that multiple services from outer suburbs are funneled into the central business district into a section of the line known as the 'loop'. During peak periods and short headways any extension to dwell time as commuters board and alight can have major consequences upon the timetable. This is especially true of dispatching empty trains at the end of the service back out into the system in a timely manner. Patronage of the system has risen dramatically, 37.6% over the last ten years (Allsop 2007). During periods of high patronage passengers will bunch in the vestibule areas and occlude the doors. This makes boarding and alighting more difficult. The further apart the doors the more reticent passengers are to move into the aisle for fear of being trapped at the station they wish to alight.

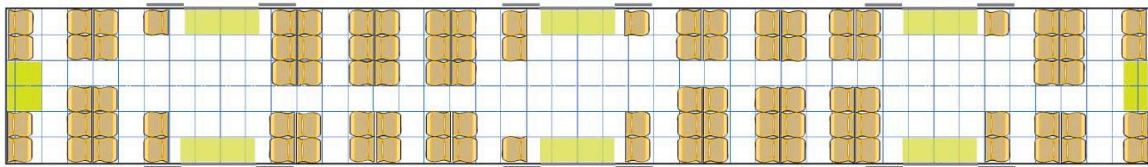
In 2008 Connex in collaboration with industry consultants sought to determine what could be done about this issue. The Comeng model of train (Figure 7), which is the most populous of the fleet (187 three car units), was used as the benchmark. This design of carriage has been in service since 1982 but was refurbished in 2000-2003. The capacity of this model is 289 seated across a three-car set, which consists of two motor-cars (slightly less seating due to drivers cab) and one trailer car.

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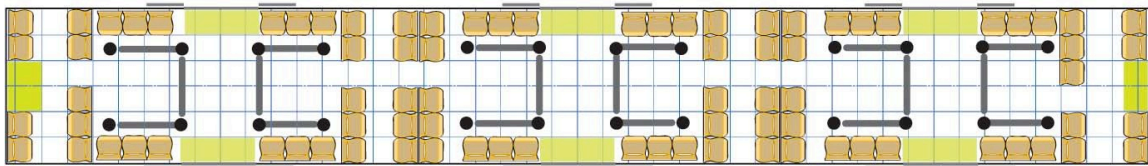
The study considered four interior arrangements of the carriages. In each case there was a reduction in seating capacity and a corresponding increase in standing room. The researchers used a standard dwell time calculation model to determine the resulting benefit of each layout. To do this a number of assumptions and considerations were put into the formula. For example in order to make useful comparisons the number of boarding, alighting and through passengers were kept the same for each layout tested. Not unexpectedly these calculations revealed that the layout with the largest number of seats removed offered the best improvements in dwell time (Figure 7).

Figure 7: A Comeng train before and after vestibule seat alterations and hand hold positions were re-appraised. Authors' diagram.

Original Comeng Layout (Trailer car)



Proposed Comeng Layout (Trailer car)



In addition to the raw mathematics of the analysis, Connex also investigated methods that might encourage passengers to move deeper into the carriage between doors. The existing Comeng trains only provided handrails in the vestibule area. These are limited to above the door and along the edge of the draught screen. This positioning encouraged passengers to occlude the door in the 'sentry position' if they could not readily move on into the carriage to locate a seat. Grab handles are located on top of the seats but they accommodate only one passenger at a time. This contrasts with a vertical handrail that might provide stability for more than one individual standing adjacent to each other. The 3+2 layout also suffers from the 'abandoned middle seat issue'. Even in trains with high loads and numerous standing passengers the central seat may remain unoccupied.

3.1 Conclusions to the Melbourne initiative

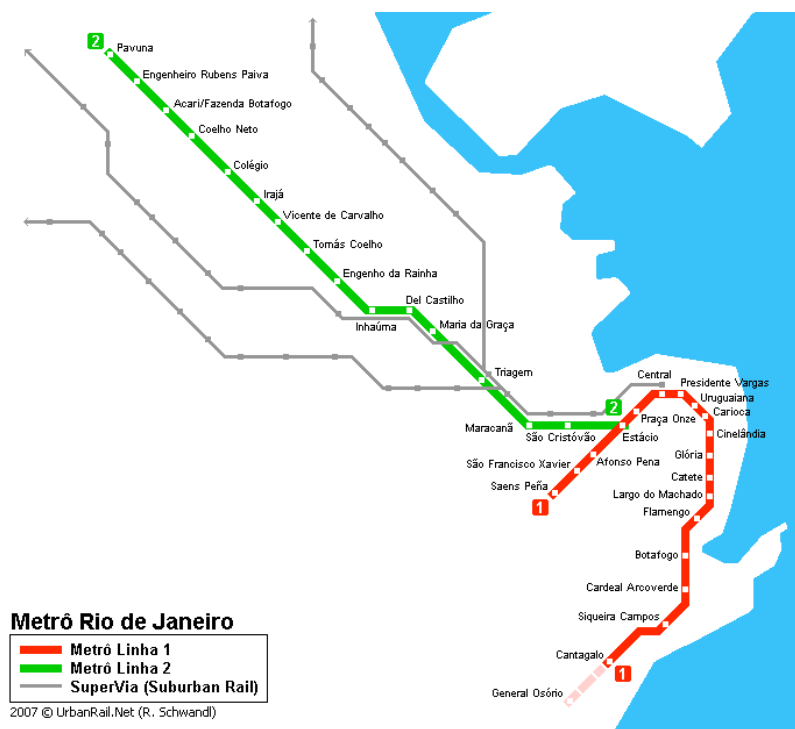
The Melbourne study carried out by Connex concluded that ceiling longitudinal handrails located within the carriage would draw passengers away from the doors and further into the carriage. It was also proposed that more longitudinal seating adjacent to the vestibule would improve passenger flow. The extent to which the TOC is prepared to remove seats is a significant political and public relations issue. More standing passengers also has one other implication; in order to mitigate the risk of injury to passengers in the event of an accident trains are obliged to reduce their operating speed, again creating consequences for network capacity.

As part of the 2008 Victorian Transport Plan, 38 new 6-car Xtrapolis trains have been procured. The seating layout will be 2+2. The new current incumbent TOC (Metro Trains Melbourne) are required to alter the seating layout of the Comeng fleet to 2+2 seating, and as an initiative directed upon the platform side the TOC has introduced more staff at major stations to encourage flow and passenger movement.

4. Duel platform boarding and alighting – Rio de Janeiro

Rio de Janeiro is the second largest city in Brazil. It has a mountainous topography that makes travelling by any surface mode a time-consuming task. Rio Metro was opened in 1979 as a response to traffic congestion and pollution. To begin with there were only five stations; Praça Onze, Central, Presidente Vargas, Cinelândia, and Glória, between them the system covered a length of only 4.3 kilometres. By 2009 the length of the system had stretched to 37 kilometres with 19 stations across two lines. Compared to municipal buses, the dominant mode in South America, Rio Metro carries only a very small percentage of passenger trips (4% or 600,000 passengers per day). However the density of the stations in the central area coupled with two major interchanges between the two lines (Estacio and Botafogo) the system is vulnerable to crowding.

Figure 8: Map of Rio De Janeiro metro system



A key feature of these interchange stations and indeed three others (Carioca, Saens Peña, and General Osório) is that they have side and island platforms that facilitate boarding and alighting on opposite sides of the train. The dwell time components of a Rio Metro train include the opening of doors first on one side of the train (the side platform) and then some few seconds later doors open on the opposite side of the train where passengers board from the island platform. It can be surmised that while the door function time has lengthened to accommodate the delay between releasing alighting passengers and introducing boarding ones the conditions for severe occlusion have been removed as the boarding and alighting

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passengers are moving in the opposite direction. This apparently makes dwell times more consistent through the day (Costa B & Costa F 2010).

Fig 9: Dual platform boarding. Flickr open source image.



This type of boarding and alighting arrangement is not unique amongst the worlds railways, but it is uncommon. This type of arrangement is normally found at airport shuttle stations or at the termini of large suburban networks, for example Homebush station in Sydney.

The motor-car carriages can accommodate a capacity of 351 passengers, however only 36 are seated. Trailer carriages can accommodate a maximum of 378 passengers with only 38 seated. A set can compose between four and six carriages. In six-passenger car configurations the maximum number of passengers that can be transported is 2,268. (Costa B & Costa F 2010).

The interior arrangement of the carriages is open with few seats. Seating is arranged with longitudinal seating positioned opposite transverse seating. Each longitudinal seat has a handle to assist passengers standing up. There are vertical stanchions from ceiling to floor for standing passengers. The vestibule area is largely clear of impediments but for a grab pole arrangement that comes down from the ceiling to form a 'cradle' for vestibule standing passengers. There are three doors per side each two metres wide (Figure 10).

Figure 10: Interior of Metro Rio trailer carriage seating 38. Authors' diagram.

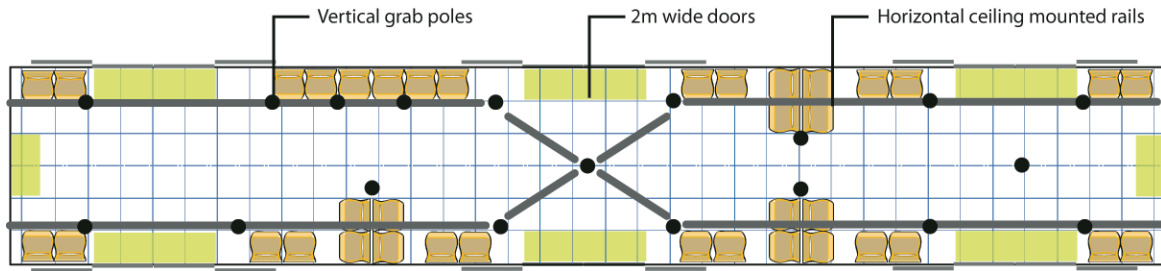


Figure 11: Interior of a Rio Metro motor-car carriage. Flicker open source image.



4.1 Conclusions to the Rio system

Since Rio Metro is only thirty years old it has not gone through any design reiterations associated with a recent increase in patronage. So there are no other carriage types to compare with. While passenger trip times are short (below 20 minutes) it is reasonable to suppose that a carriage design with a diminutive number of seats might continue. However with an expansion of the network underway and journey times then set to increase, the operator may be forced to consider increasing the number of seats per carriage.

Metro Rio has a couple of other interesting features. The network runs women only carriages at peak times. There is also a large presence of staff at all stations for assistance and safety, assisting wheelchair boarding as well as cleaning at each terminal. The presence of staff has been significant in contributing to metros high levels of safety and cleanliness in a city that has a reputation for high levels of crime.

5.0 Comparing networks

The table on the following page shows that high overall passenger capacity is analogous with a low number of seats in each carriage. What can also be inferred is that Melbourne Metro has the double problem of requiring the most seats (with potentially the longest passenger journeys) while accommodating a high overall passenger capacity. Stockholm and Rio can function as a short journey transit system whereas Melbourne Metro has to perform as both a short journey metro and to all intents and purposes a regional train as well.

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Table 1: Network comparisons. Authors' table

		Network system length	Track gauge	Carriage passenger capacity	% of capacity taken by seating
Stockholm Lokaltraffik <i>(CX Trailer car)</i>	106kms	1435mm	158	16% - 20%	
Rio Metro <i>(Trailer car)</i>	47kms	1600mm	378	9.5%	
Melbourne Metro <i>(Comeng Trailer car)</i>	372 kms	1600mm	254	34%	

The track gauge reference in Table 1 indicates the general extent of the carriage dimensions. Although Rio and Melbourne rolling stock have similar widths, Melbourne has longer carriages and Stockholm has both narrower and shorter rolling stock therefore restricting its potential capacity.

6.0 Conclusion

Overcrowding is one of the key challenges facing transport operating companies in cities around the world. The effects upon timetable performance and dwell time are significant. It will increasingly constrain network capacity, service delivery and diminish positive passenger perceptions of the mode.

Three different networks have been discussed in this paper each with slightly different approaches to the problem. All have concluded that for carriage capacity to increase, within the constraints of gauge and length, there needs to be an increase in the number of standing passengers at the expense of seating. It has been shown by successive surveys in various parts of the world that amongst different variables passengers perceive comfort as having a seat, especially if the journey is beyond 20 minutes.

The implications of this paradox especially for networks in Australia where short trip metro's morph into semi-regional long trip suburban services is that interior carriage layouts might better serve passengers if they are mixed rather than uniform throughout the set. The Authors' speculate that rather than having the same interior seating arrangements

throughout the train, that in fact specific carriages on the same six-car set could be earmarked for passengers travelling long distances, (and therefore have more seats) and other carriages largely devoid of seats for short inner city journeys. The Stockholm experiment revealed that the position of such carriages in the set is also important in their acceptance, especially in relation to station entrance and exit points. The sort of mixed seating layouts suggested would require a level of culture change and discipline from patrons to achieve aspirational levels of comfort and dwell time stability. However, the Authors' would go further in suggesting that a more radical approach to interior carriage design might include having an internal structure that can change depending upon the time of day and the passenger demand. So for example less seats during peak periods, possibly by way of folding seats and more seats available during off-peak periods when the patronage can be more easily accommodated comfortably. These observations form the basis of future on-going design work to explore these possibilities.

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