THE IMPLICATIONS OF PERSONS WITH REDUCED MOBILITY ON SPATIAL DESIGNS

L Hermant*, G Davies and K Shirley***

*Hatch Goba (Pty) Ltd, P.O. Box 3878, Tyger Valley, Cape Town, 7536
Tel: 021 911-5823; email: lhermant@hatch.co.za
**Disability Solutions (Pty) Ltd, P.O. Box 6037, Paarl, 7620
Tel: 021 872-1101; email: guy@disabilitysolutions.co.za

ABSTRACT

In this paper, the sensitivity of how pedestrian composition, in terms of Persons with Reduced Mobility (PRM's) i.e. slower walkers including the disabled, visually impaired, elderly etc. influence the quantitative assessment of pedestrian spatial requirements within mass transit areas (such as at stations) is proposed. The study uses microscopic simulation methods for the assessment. The paper also assesses the impact that wheelchair users or Non-Ambulant Persons (NAP's) and Persons with Bicycles (PWB's) have on the design service criteria; in other words, the assessment of the reduction in Level-of-Service (LOS), due to a proportion of NAP's and/or PWB's within the pedestrian mix. The quantification thereof and the implication on universal design is discussed in terms of the need for additional infrastructure (spatial) requirements. Currently, little research has been undertaken regarding multi-modal LOS (MMLOS), or the impact of multiple pedestrian modal types on LOS; specifically, the impact of pedestrians pushing bicycles or people in a wheelchair on the standard LOS classification system. Since there is no accepted standard design methodology available for determining multi-modal level-of-service (MMLOS), the paper suggests that the resulting reduced MMLOS can be calculated on the basis of the reduced space-density (*M*) experienced by each individual person based on the additional space requirements in accordance with "*equivalent*" pax factors specifically defined in this paper. It is the intention that the paper will provide a greater awareness of the design considerations within industry when considering Special Needs Persons (SNP's), NAP's and/or PWB's and offers quantitative guidance towards calculating appropriate spatial requirements within mass transit environments as evaluated in terms of required Level-of-Service (LOS) criteria. A discussion on shortcomings and limitations of the study is included and further work required is suggested.

1. PROBLEM STATEMENT

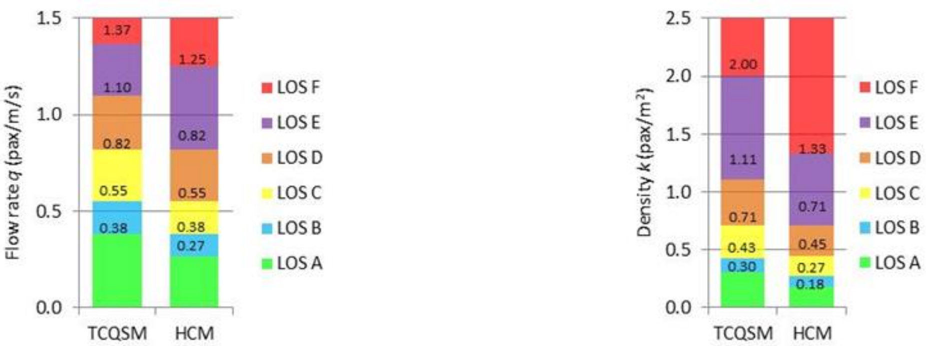
Spatial planning for mass transit station facilities requires the dynamic analysis of infrastructure space. Pedestrian dynamics influences design, which may be affected if significant PRM movement is expected, particularly with regard to maintaining certain LOS standards during operational conditions as usually mandated by mass transit authorities.

Within this context, this research attempts to determine how a mixed population, including PRM's, impact on spatial design requirements in order to maintain Fruin (1971) LOS standards, specifically developed for the able-bodied population.

2. INTRODUCTION

Estimation of pedestrian LOS is the most common approach used in assessing the quality of operations of pedestrian facilities. Fruin (1971) first introduced the concept of pedestrian LOS in an attempt to provide a scale to benchmark pedestrian activity using density and flow rate. Fruin's scale makes reference to five grades, from a LOS A (unimpeded free-flow) to a LOS E (very restricted walking possible). A LOS F is not specifically defined in the table but is normally defined for conditions worse than LOS E where flow reduces to zero and walking is no longer possible.

Fruin's measurements are however, based on pedestrian street environments and not in mass transit environments where lower LOS can be expected to be tolerated for short durations. A comparison of the Highway Capacity Manual (HCM) LOS boundary values (TRB 2000), adopted from Fruin and the Transit Capacity and Quality of Service Manual (TCQSM) LOS boundary values (TRB 1999a), adopted specifically for public transport facilities, is indicated in Figure 2.1 for walkways. From the graphs, it is evident that the TCQSM boundary values allow for greater flow boundaries when compared to HCM; see Figure 2.1(*a.*) for flow rate LOS boundaries and Figure 2.1(*b.*) for density LOS boundaries.



(a.) Flow rate (q) LOS bandwidths *(b.) Density (k) LOS bandwidths*

Figure 2.1: LOS boundary differences between HCM (Fruin) and TCQSM guidelines for walkways

3. PAST RESEARCH ON LEVEL-OF-SERVICE

There are a number of criticisms regarding pedestrian LOS. Both Naderi (2003) and Zhang (2004) are critical of the Fruin LOS scale since they argue that this concept was initially developed for vehicles, which ignores the relevance of human factors and is therefore, an oversimplification. Zhang (2004) prefers the notion of a gradual LOS transition "*which correlates better with human perception of LOS*" instead of rigid boundaries. Khisty (1994) and Henson (2000) both argue that there are additional environmental measures affecting perceived LOS including comfort, convenience, safety and security factors. According to Still (2000) and Pheasant (2002), Fruin's selection of body size data is over-generous in terms of body size and clothing viz. attired in thick clothing more suited to cold temperatures not applicable to warmer environments. The Fruin LOS guidance, which has been adopted by the HCM guideline document (TRB 2000), is also unfortunately applicable for uni-directional movement only and does not take into account bi-directional or cross-flow movement (Rouphail *et al.* 1998; Blue and Adler 2000) or the extent to which PRM's in the pedestrian mix influence the LOS (which is the subject of this paper).

4. LEGISLATION AND GUIDELINE DOCUMENTATION

The Constitution of Republic of South Africa, 1996 (Act No. 108 of 1996) affirms democratic values of human dignity, equality and freedom for all its citizens and the State may, therefore, not unfairly discriminate against persons on the grounds of gender, age or disability.

There are various National Regulations, which incorporate these values (viz. Promotion of Equity and Prevention of Unfair Discrimination Act 2000, National Land Transport Transition Act 2000, Human Rights Commission Act 1994, Employment Equity Act 1998 and National Building Regulations and Building Standard Act 1977) that address accessibility and transport in South Africa, including various guideline documentation (e.g. DOT, 2003; SARCC, 2008 and NMT Facility Design Guidelines, 2014), which typically recommends minimum infrastructure standards and guidelines to accommodate individual PRM's in society.

However, whilst legislation adequately protects the needs and requirements of PRM's on an individual basis, consideration towards how infrastructure can accommodate or perform with such persons, in crowded situations, could not be sourced in any design guideline documentation.

5. MODELLING CATEGORIES

For the purposes of this research paper, different person types were grouped together into two main and three sub-categories of person types to be modelled as defined below:

Persons with Reduced Mobility (PRM's)	• Special Needs Persons (SNP's): Defined to consist of children between 5 and 14 years old, physically and mentally disabled, person/s laden with shopping bags (Ribbonaar *et al.* 2004), pregnant women (> two months), deaf and visually impaired, and elderly person/s 65 years and older. (Source : Stanbury and Scott, 2005); • Non-Ambulant Persons (NAP's): Defined to consist of the wheelchair users. These passengers require significantly larger area and impact the speed of surrounding passengers; • Persons with Bicycles (PWB's): Defined to consist of adults travelling with bicycles (Disability Solutions 2014, Fisher and Jenkins, 2010).
Able-Bodied Persons (ABP's)	• Able-Bodied Person (ABP's): Represents all persons falling outside the definition of PRM's;

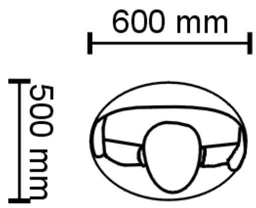
Preliminary research currently suggests that SNP's account for up to 32% of the population, identified in the 2001 Census (Stanbury and Scott, 2005).

6. SPACE REQUIREMENTS AND LOS CRITERIA

6.1 Able-Bodied Persons (ABP's)

Table 6.1 tabulates the available literature results regarding ABP space requirements in terms of increasing area. According to Daamen (2004), the minimum surface of an average pedestrian is about 0.085 m^2. Taking the 95th percentile data for males and allowing for clothing, Pheasant (2002) defined the body ellipse to be 630 by 380 mm representing an area of 0.239 m^2. Weidmann (1993) suggested that physical contact between standing persons might be avoided at densities of 0.286 to 0.333 m^2/pax.

Pedestrian guidelines produced by DOT (2003) suggest a body ellipse of 600 x 500 mm with a total area of 0.30 m^2 for a standing adult. In practice, Weidmann typically found a density of between 0.345 to 0.5 m^2/pax for waiting pedestrians. Pushkarev & Zupan (1975) noted that pedestrians prefer a body buffer zone space of 0.27 to 0.84 m^2, where space needed to make a step is included.



Body Ellipse (Source: DOT, 2003: A.5.2)

For the purposes of this study, a minimum design space of 0.5 m^2 around each pedestrian was used.

Table 6.1 : Pedestrian Area Profiles for Able-Bodied Persons (ABP's)

Description	**Area (m^2) & LOS* (in brackets)**	**Source**
Minimum surface area (without bulky clothes and baggage)	600 x 145 0.085 - 0.087 (F)	Amos. J (2007), Daamen (2004)
95th Percentile Male (with 25 mm for clothing)	630 x 380 0.239 (F)	Pheasant (2002)
Density where physical contact may be avoided	0.286 – 0.333 (F)	Weidmann (1993)
Standing Adult (practical minimum for standing person)	600 x 500 0.300 (F)	DOT (2003)
Practical density for waiting pedestrians	0.345 – 0.5 (F)	Weidmann (1993)
Preferred pedestrian "*Buffer*" Space for Adult (including space for step)	0.27(F) - 0.84 (E)	Pushkarev & Zupan (1975)
Optimum Density	0.556 – 0.769 (E)	Virkler & Elayadath (1994)
Minimum Design "*Buffer*" Space for Adult	867 x 867 0.750 (E)	TRB (2000)

**: LOS based upon TCQSM Platform area walking standard.*

6.2 Non-Ambulant Persons (NAP's)

The UK Department for Transport conducted a survey into occupied wheelchair sizes, which collected measurements for all dimensions of wheelchairs (Leake *et al.,*1989) and found that the 50th percentile for the length and width of wheelchairs was1116 mm and 612 mm respectively.

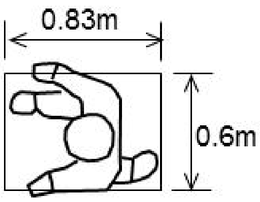
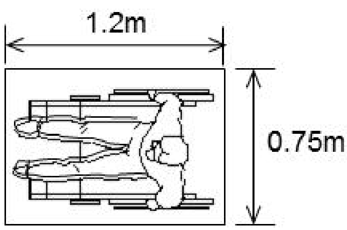
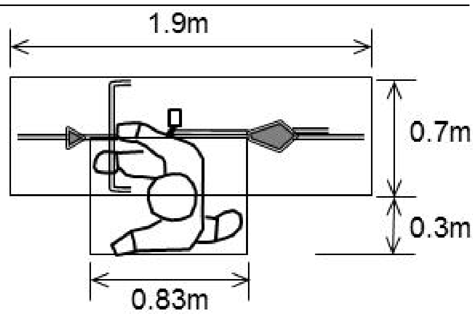
The minimum area needed to accommodate a single, stationary wheelchair and occupant is 1 200 mm by 750 mm (U.S. Architectural & Transportation Barriers Compliance Board, 1998), which was used in this study. A minimum width of 1500 mm x 1500 mm would allow a wheelchair to make a 180 degree turn in a circular motion (DOT, 2003).

6.3 Persons with Bicycles (PWB's)

Various types and sizes of bicycles are available, ranging from the children's bicycles to the larger adult cycles. For design purposes, however, conservative dimensions are selected, which provides for most cyclists. DOT, 2003 provides dimensions for a standard design bicycle that is 0.6 m wide (at the handlebars) and 1.8 m long. For the purposes of this study, additional buffer clearance of 0.1 m is added.

Table 6.2 summarises the area profiles for the three modelled person groups and shows the "*equivalent*" Pax factor based on the relationship to the unit area of an ABP.

Table 6.2 : Area Profiles for ABP, NAP and PWB Categories

Type	ABP	NAP	PWB
Dimensions			
Area	0.498 m^2/Pax	0.900 m^2/Pax	1.579 m^2/Pax
Equiv. Pax Factor	1x	1.807x	3.171x

6.4 LOS Criteria

Table 6.3: LOS Criteria (TRB, 1999)

LOS	Platform Walking Area Density (m^2/pax)
A	> 3.3
B	2.3 – 3.3
C	1.4 – 2.3
D	0.9 -1.4
E	0.5 - 0.9

F	< 0.5

The Level of Service (LOS) thresholds from the Transit Capacity and Quality of Service Manual (TCQSM), (TRB, 1999) were used in the assessments (refer to the Table 6.3).

These differ to the thresholds provided in the HCM2000 and older Fruin guidelines, specifically to account for pedestrian movements within public transit areas, where conditions that are more crowded are to be expected and tolerated.

7. IMPACT OF SNP'S ON LOS METRICS

To test the impact of variations in the pedestrian composition and ultimately on spatial LOS, a sensitivity analysis was undertaken on the staircases at Khayelitsha Railway Station, Cape Town used as a Case Study station (Goba, 2009). This station formed part of the national stations upgrade programme embarked in 2007 by the Rail Authority.

7.1 Pedestrian Composition

Three scenarios were tested using different compositions of pedestrians, and are summarised in Table 7.1.

Table 7.1 : Pedestrian Composition Scenarios

Pedestrian Type	Scenario 1	Scenario 2	Scenario 3	Desired Speed*[1] (m/s)
Male ABP	45%	45%	45%	0.97 – 1.61 m/s
Female ABP	34%	34%	34%	0.72 – 1.19 m/s
Aggressive ABP*[2]	20%	16%	11%	0.97 – 1.61 m/s
SNP	1%	5%	10%	0.11 – 1.14 m/s

*[1] *The "Aggressive" category of pedestrians has a greater acceleration parameter of 3.5* m/s^2 *compared to normal pedestrians who have an acceleration parameter of 1.5* m/s^2*.*
*[2] *Walking speed under unhindered (or "free-flow") conditions.*

Note that the microscopic model (VISSIM) uses a stochastic walking speed profile for each of the pedestrian types modelled. Walking speed profiles are all normally distributed ranging from a fast 1.61 m/s to a slow 0.72 m/s for the ABP pedestrian types in accordance with observations made by Hermant (2012). For the SNP group, a normally distributed speed profile was specifically developed around the 0.8 m/s mean walking speed with a range of 0.11 to 1.14 m/s. Using this composition profile, 66% of passengers fall within the 1.15 to 1.5 m/s category.

7.2 Sensitivity Results

This study assessed the impact on the busiest platform Staircase “”C” (see Figure 7.2) at Khayelitsha station during the morning peak (15-min period), with various proportions of SNP and aggressive persons as indicated. Over the 15-min period (06:30 to 06:45), a total of 2,018 passengers are modelled, 1,858 of which board and 160 passengers alight the twelve 8M coaches.

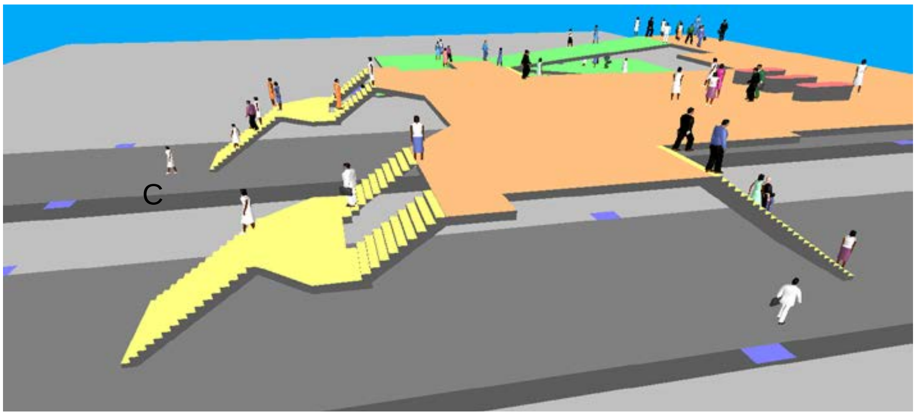


Figure 7.2: Khayelitsha Station Layout showing Staircase "C" (VISSIM model)

Figure 7.3 shows the longitudinal time series flow rate graph (in terms of p/m/min) for the modelled sensitivity results collected on the 3.3m wide staircase during the AM peak 15-min (900 sec) period.

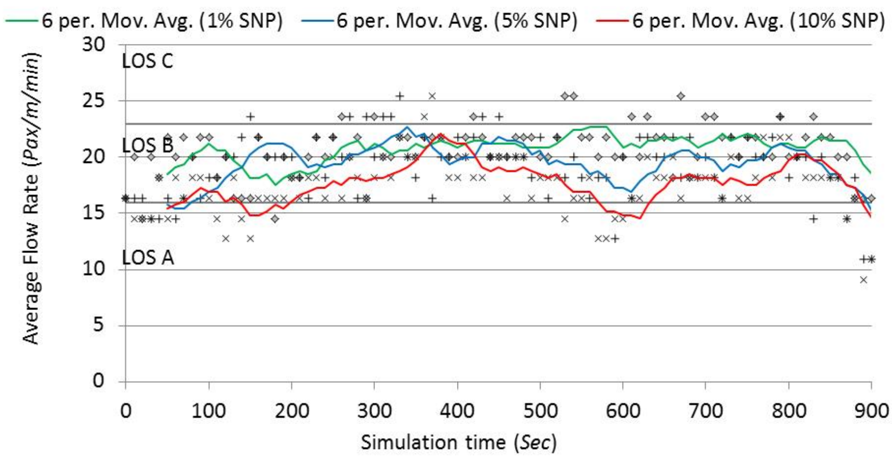


Figure 7.3: Longitudinal Plot of Average Flow Rate (q) for three SNP Scenarios at Staircase "C" showing the moving average profiles over 60 sec intervals

Pedestrians influence each other in their walking behaviour either with mutual or reciprocal action. They need to avoid or overtake each other to be able to maintain their speed, they need to change their individual speeds and direction and sometimes they need to stop and wait to give others the chance to move first. In crowded situations, they need to maintain their distance/headway with regard to other pedestrians and surroundings to reduce their physical contact with each other.

It is apparent from the simulation output graph (see Figure 7.3) that greater SNP proportions improves flow rate levels of service for the entire duration of the simulation. This is contrary to what is intuitively expected when one considers SNP's in a pedestrian environment. The reason for the improvement in flow rate levels of service (LOS) is the reduction in walking speeds of SNP pedestrians, which distributes the pedestrian arrival rate at infrastructure elements and thereby, spreading the congestion level.

Of course, it can be assumed (without testing) that there is a critical point at which further increases in SNP composition begins to introduce congestion levels again.

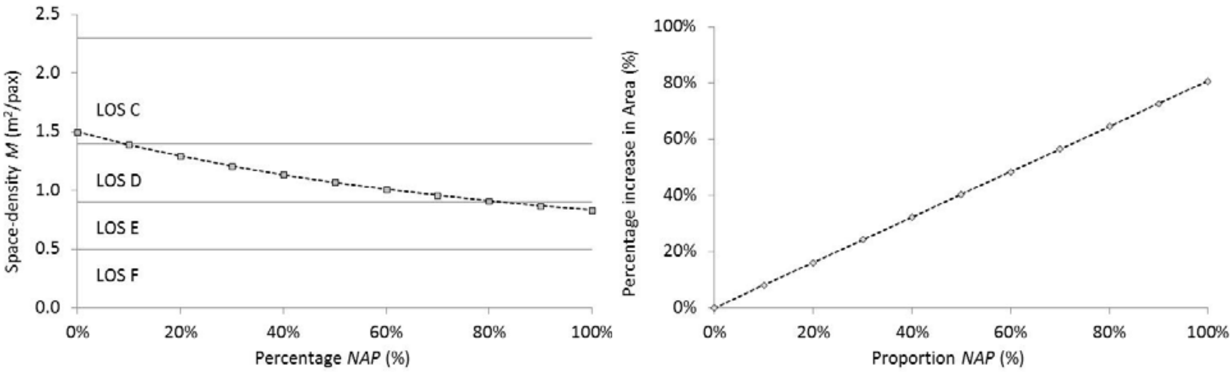
8. IMPACT OF NAP'S ON LOS METRICS

For the purposes of illustration, a uni-directional passenger density of 100 pax evenly distributed over the 150 m^2 area is assumed, which provides a LOS C density condition in terms of the Platform Walking TCQSM standard (TRB, 1999b).

Figure 8.1(*a.*) below graphically shows the decline in platform space-density (*M*) with increasing *NAP* percentages for a 100 pax crowd over 150 m^2 of platform space. The graph shows that LOS D conditions are triggered with approximately 10% *NAP*'s. Without any *NAP*'s, the 100 *ABP* pax occupy a space-density (*M*) of 1.5 m^2/pax. With increasing *NAP*'s, the Platform space-density (*M*) reduces in accordance with the following formula:

$$M = \frac{Area}{ABP + (1.807\,NAP)} \tag{1}$$

The last two columns of the table indicate the area required to maintain the LOS calculated for zero *NAP*'s in meter-square and percentage respectively. The graph shown in Figure 8.1(*b.*) below demonstrates the relationship between the proportion of *NAP*'s in a crowd and the percentage increase in space required (over and above the 150m^2 available) to achieve an equivalent space-density LOS. By way of explanation, the relationship shows that for a 150 m^2 area designed for say 100 pax (i.e. LOS C condition), that should 10% of this crowd (or 10 pax) be in wheelchairs, then an additional 8.1% space (or 12 m^2) must be provided in order to accommodate both modes (i.e. 90 *ABP* pax and 10 *NAP*'s) simultaneously at the initial LOS C level.



(a.) Space Density (M) | *(b.) Percentage Area Required*

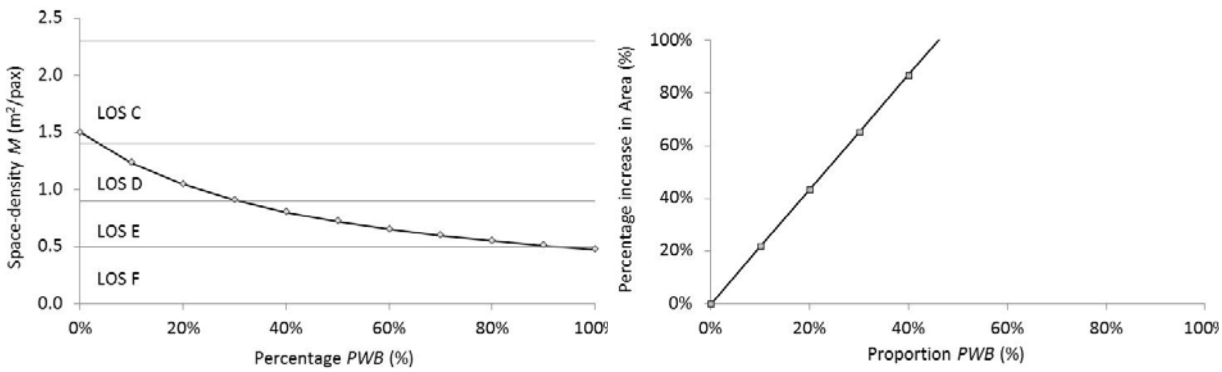
Figure 8.1: Percentage *NAP's* and Additional Space Requirements

9. IMPACT OF PWB'S ON LOS METRICS

A passenger volume of 100 pax evenly distributed over the 150m^2 area is assumed for calculating *ABP* LOS, providing the initial space-density (*M*) of 1.5 m^2/pax. Figure 9.1(*a.*) graphically shows the decline in platform space-density (*M*) with increasing *PWB* percentages and declines at a greater rate than the *NAP* graph (shown in Figure 8.1 (*a*.)), due to the greater pax equivalency factor allocated to *PWB*'s. In this instance, LOS D conditions are triggered with less than 4% *PWB*'s and deteriorates further into LOS E with around 30% *PWB*'s prevalent in the crowd. With increasing *PWB*'s, the Platform space-density (*M*) reduces in accordance with the following formula:

$$M = \frac{Area}{ABP + (3.171\ PWB)} \qquad (2)$$

The graph shown in Figure 9.1(*b.*) demonstrates the greater spatial requirements that *PWB*'s impose on designs when compared to designing solely for *NAP*'s. In this instance, should 20% of this crowd (or 20 pax) be with bicycles, then an additional 43.4% space (or 65m^2) must be provided in order to accommodate both modes (i.e. 80 *ABP* pax and 20 *PWB*'s) simultaneously at the initial LOS level.



(a.) Space Density (M) | *(b.) Percentage Area Required*

Figure 9.1: Percentage *PWB's* and Additional Space Requirements

10. MULTI-MODAL IMPACT (INCLUDING BOTH NAP'S AND PWB'S)

Since there is no accepted standard design LOS criteria available for a multi-modal (i.e. combination of *ABP*, *NAP* and *PWB*'s) level-of-service (MMLOS), the resulting MMLOS is calculated based on the reduced space-density (*M*) experienced by each individual person based on the additional space requirements in accordance with the equivalent pax factors as follows:

$$M = \frac{Area}{ABP + (1.807\ NAP) + (3.171\ PWB)}$$

Figure 10.1 shows two scenarios indicating the relationship between increasing person (pax) volumes and decreasing space-density for able-bodied persons (*ABP*) and for a 78%:2%:20% *ABP*:*NAP*:*PWB* combination scenario over a fixed 100 m^2 platform area.

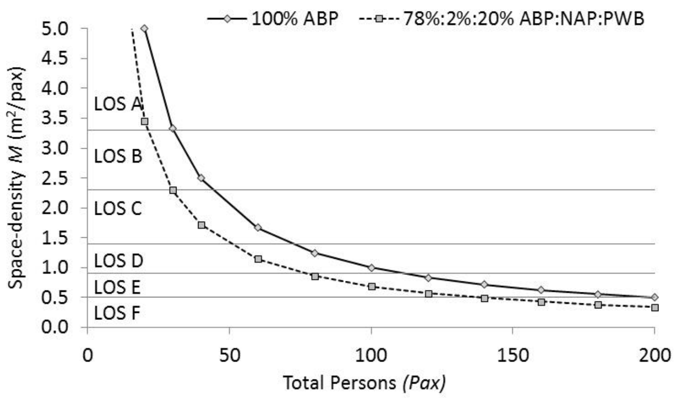


Figure 10.1: Space Density (*M*) LOS for increasing Pedestrian Volumes

Figure 10.1 shows that 60 *ABP*'s could comfortably operate at a space-density (*M*) of 1.7 m^2/pax (LOS C) but would deteriorate to an unacceptable LOS D condition (for the same available space) for the multi-modal scenario. Alternatively, to maintain a MMLOS C, only 40 persons from this group can be accommodated within the 100m^2 area.

11. LIMITATIONS OF THE STUDY AND FUTURE WORK

It should be noted that this study is not challenging the Fruin vs TCQSM vs HCM Level-of-Service criteria, but merely suggests how to incorporate PRM's (with greater influence areas) within the existing classification system.

The impact of persons with walking sticks, crutches, walking frames, pushing prams or carrying large luggage on the LOS criteria spectrum is not included in this work, nor are adults being accompanied by young children. Persons with visual impairments accompanied by guide dogs are also excluded from the study.

The LOS calculations in this paper refer to persons waiting on a platform and therefore, is a static density calculation aligned in a uni-directional only and excludes the impact of bi-directional and dynamic traffic. In a dynamic situation, more space allocation is required for the mobility for all users, particularly around wheelchair users, with consequently more onerous implications on LOS calculations.

The study is to be used as an indicative design guide only, until further detailed work is undertaken and calibrated against real time observations.

The designer is cautioned to use the results to account for emergency design conditions.

12. CONCLUSIONS AND RECOMMENDATIONS

This paper has highlighted that best practice design requires movement of PRM's to be fully factored into the design process and, depending on local circumstances, may influence and alter design guidance.

The results of this research have highlighted that Passengers with Reduced Mobility (PRM's) can no longer be ignored in the field of passenger flow modelling. Research in this area, however, is far from complete. Collecting data in order to estimate the numbers, areas and speeds for potential new PRM pedestrians in micro simulation models, while an important first step, is in some ways the simplest part of the process towards accurate modelling of all pedestrians.

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