A METHODOLOGY FOR THE DETERMINATION OF ACCESS GATE/TURNSTILE UPSTREAM SPATIAL REQUIREMENTS AND LEVELS OF SERVICE

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ABSTRACT

In this paper, a new innovative way for determining access gate (or turnstile) requirements at mass transit stations as well as upstream spatial requirements, tested using microscopic simulation within mass transit environments, is presented.

Turnstile requirements are currently based on the passenger demand being matched by the turnstile service flow rate capacity. Whilst this may be adequate for low volume stations, it is argued that this method should not be applied to busier stations where excessive queuing and crowding occurs. Design guidelines provide little guidance in this regard, except to provide queuing density ranges for the various LOS (Level of Service) criteria, which is difficult to calculate.

To date, the author has developed a queue space-density (M) versus volume/capacity (v/c) relationship for the determination of turnstile gate requirements, but this method is entirely dependant on a user pre-selected measurement area. Since queue density parameters are impractical to calculate due to the varying nature of human queuing behaviour at turnstiles, the research undertaken has contributed towards developing a methodology for determining the number of turnstiles using a more simplified queue density vs. v/c power relationship and also proposes using associated average person delays as an alternate method to determine turnstile requirements. The research has also identified that infinite queues begin to develop when v/c ratios exceed 0.92.

The aspect of spatial requirements upstream of turnstiles has also been addressed in this paper and space-density (M) vs. v/c relationships for various floor areas have been used as assessment benchmarks.

Keywords: microscopic pedestrian simulation, turnstile requirements, spatial level-of-service (LOS)

INTRODUCTION

Whilst a significant amount of research has been undertaken on vehicle queuing theory, little has been done on quantifying the competitive human dynamic at turnstiles[1]. Typically, clients insist on an operational level of service (LOS) for all infrastructure items (including turnstile operations), and a LOS C/D is usually considered acceptable, but quantitative guidelines do not exist as to how to calculate this LOS, especially at turnstiles. Current practice is to provide as many turnstiles as necessary to match the peak pedestrian demand based on turnstile capacity, but this paper aims to prove that this is erroneous practice leading to congested conditions.

This paper presents a new method of determining turnstile requirements based on average pedestrian delay rather than on queue space-density and further aims to provide spatial requirements upstream of the turnstiles to contain the queuing crowding effect within the required LOS bandwidth.

The remainder of the paper is organised as follows: An introduction is given to the current techniques and problems experienced using microscopic[2] (micro) simulation when modelling turnstile behaviour. The “gap” methodology of turnstile assessment is then described together with how the appropriate sizing of the gap is achieved. This is followed by describing the assessment criteria to be used when evaluating turnstile operations and introduces the delay method of assessment together with how spatial requirements upstream of turnstiles can be calculated in order to adequately accommodate crowding effects.

A concluding statement is then made where the new assessment methodology described in the paper is summarised and shortcomings and further investigation is highlighted

SIMULATION OF TURNSTILE OPERATIONS

Methods to Simulate Turnstile Operations

Previous micro simulation work by the author (Hermant *et al.* 2009 and Hermant *et al.* 2010) revealed that turnstile throughput follows a linear relationship with bottleneck[3] gap. This finding led the author to use bottleneck gap widths to simulate turnstile operation for uni-directional pedestrian movement only.

Turnstile modelling using micro simulation techniques (in this case, using VISSIM[4]) can be performed via different means. This section analyses the benefits of modelling turnstile operation using two distinct methods, viz. either as individual turnstile gates with separate

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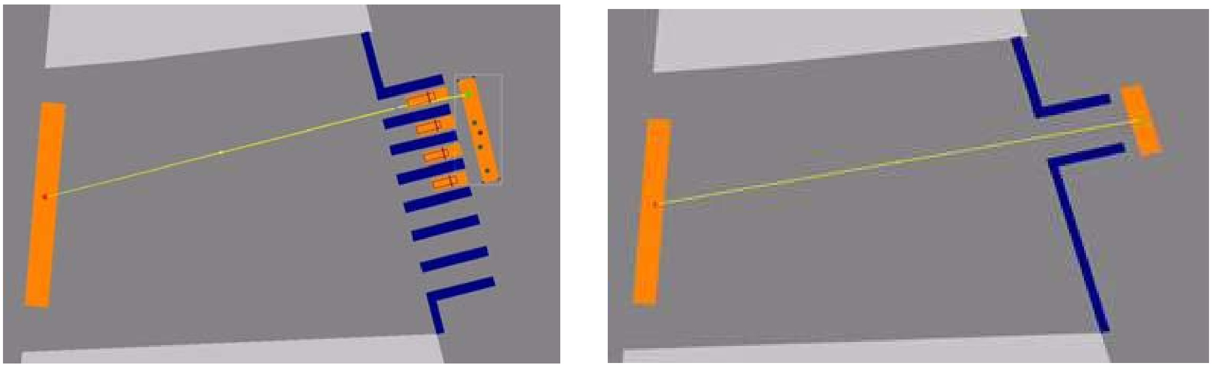
[1] *For the sake of consistency, reference to the term “turnstiles” will be made throughout this paper, although more recent terminology such as “access gates” or “ticket verification points (or TVP’s)” are also applicable.*
[2] *The method of modelling used based on the dynamic behaviour of individual pedestrians rather than as an aggregate volume.*
[3] *A narrowing of a thoroughfare, causing a reduction in pedestrian throughput or flow rate.*
[4] *Verkehr in Städten - Simulation model (Microscopic modelling software)*

detectors and signals as shown in Figure 1(*a.*); or as a gap between two obstacles as shown in Figure 1(*b.*).



(a.) Separate access gates *(b.) Gap method*

Figure 1 – Turnstile modelling techniques (Source: Hermant *et al.* 2009)

Modelling individual turnstiles relies upon adding a pedestrian area in front of each of the turnstiles, to where all pedestrians are assigned before continuing through the turnstile. A routing decision is then introduced from this area distributing them between each of the turnstiles.

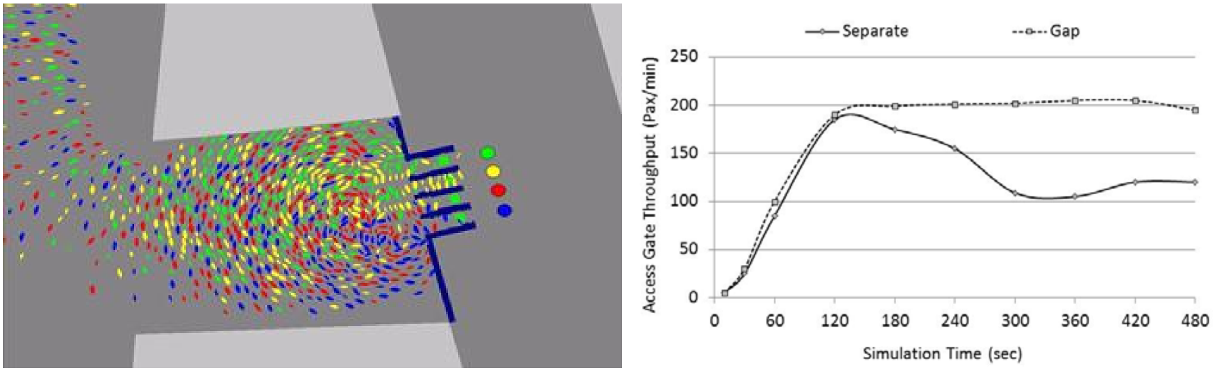
Problems with Simulating Pedestrian Behaviour through Turnstiles

Due to the “repulsive and attractive” behavioural nature of pedestrian social force models (such as used in VISSIM), the width of the actual turnstile influences the behaviour of the pedestrian and ultimate throughput pedestrian flow rates do not match actual output experienced in reality.

Also, due to the nature of microscopic modelling, simulated pedestrians tend to take the shortest path. Accordingly, there is therefore a need to assign a separate route choice for each turnstile in order to prevent all pedestrians using the closest turnstile, which is unrealistic. In crowded conditions, the crossing pedestrian conflict forced upon the model may require that a different turnstile than the one allocated be used to optimally reach the destination.

This phenomena is demonstrated in Figure 2(*a.*), showing the allocation of the approaching pedestrians to each of the four coloured turnstile gates, where the inefficiencies of turnstile selection is immediately apparent. Figure 2(*b.*) shows how this inefficiency is manifested in the variable pedestrian throughput rates achieved at high volumes using the separate turnstile modelling methodology when compared to the Gap method.

With reference to Figure 2(*b.*), the benefit of the “gap” methodology over the “separate” turnstile methodology is clearly evident since the intended design throughput (200 pax/min) is consistently achieved throughout the simulation for the *v/c* > 1 condition, in contrast to that achieved using the “separate gate” method, thus demonstrating the suitability as a method for modelling.



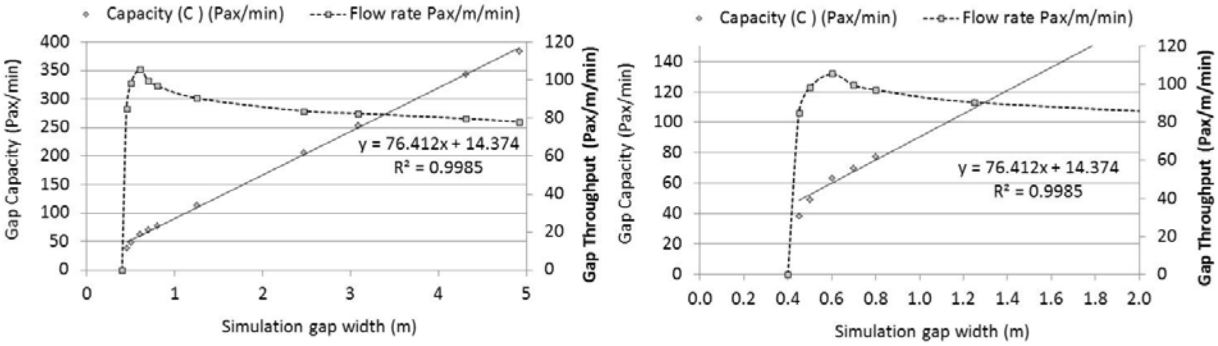
(a.) Pedestrian conflict dynamic *(b.) Access gate throughput comparison*

Figure 2 – Turnstile gate modelling techniques (Source: Hermant *et al.* 2009)

Determining the Turnstile Gate Gap

As already indicated, modelling the actual width of individual turnstiles will not replicate the true pedestrian throughput and will underestimate true capacity and will ultimately lead the designer to oversupply the required number of turnstiles. This modelling shortcoming, together with the crossing pedestrian conflict dynamic, suggests that modelling turnstiles as a single “wide” access gate is the preferred method of simulating turnstile operation, as demonstrated in Figure 1(*b.*).

It emerged from a micro simulation exercise undertaken by the author, that pedestrian throughput is directly proportional to the access gate gap width. This statement has been derived from a simulation experiment where a large pedestrian demand (at $v/c > 1$), were directed through gaps of variable size. Figure 3 shows the results of this study plotting pedestrian throughput per minute against the width of the modelled gap as well as throughput in per metre width terms. Figure 3(*a.*) shows the results for gap widths up to 5 m and Figure 3(*b.*) shows the results up to 2 m.



(a.) Gap vs. throughput results (0 to 5 m) *(b.) Gap vs. throughput results (0 to 2 m)*

Figure 3 – Turnstile gate gap capacities

Both graphs show the linear relationship between the turnstile gate gap width and pedestrian throughput for gaps greater than 0.45 m. In VISSIM, no pedestrians can pass through a gap of less than 0.4 m.

Also evident in both graphs is the peaking of the flow rate per metre curve below gap widths of 1.0 m. From the simulation experiment, it was found that maximum flow rate per metre widths occurred at 0.60 m before the curve "normalised" at wider widths. The reason behind this is due to a well-known phenomenon called "zipping"[5] described in greater detail in the following section. Table 1 tabulates the values obtained from the simulation experiment and indicates where the "zipping" effect is observed.

Table 1 – Capacity and Flow Rate results for various Bottleneck Gap Widths

Gap (m)	**Demand (*v*) (Pax/min)**	**Capacity (*c*) (Pax/min)**	***v*/*c***	**Flow rate Pax/m/min)**	**Comment**
0.45	50.33	38.33	0.00	85.19	Single file
0.50	66.75	49.29	1.34	98.57	Zipping Occurs
0.60	83.73	63.38	1.37	105.64	
0.70	83.90	69.76	1.33	99.66	
0.80	83.95	77.67	1.20	97.08	
1.25	154.78	113.22	1.08	90.57	
2.47	253.13	206.97	1.37	83.79	No zipping, multiple lanes
3.08	315.57	254.38	1.22	82.59	
4.31	421.30	344.25	1.24	79.87	
4.92	420.33	384.43	1.22	78.14	

Lane Formation and Gap Throughput

The previous section has shown that there is a linear relationship between gap width and flow throughput in pax/min. However, when flow rate is represented in terms of pax/min/m, there is a noticeable improved performance for gaps between 0.5 to 1.25 m which occurs as a result of the "zipping" effect.

As shown in Figure 4(*a.*), at bottleneck gaps of less than 0.5 m, the pedestrian throughput dynamic is strictly single file only. Once the bottleneck gap increases, pedestrians then are able to "self-organise" themselves into an overlapping zip-like fashion as evident in Figure 4(*b.*). At bottleneck gaps greater than 1.25 m, pedestrians choose to maintain their interpersonal space and the "zipping" effect no longer occurs as shown in Figure 4(*c.*).

(a.) single File only (0.45 m) *(b.) Zipping (0.5 to 1.25 m)* *(c.) Multiple Lanes (> 1.25 m)*

Figure 4 – Bottleneck Behaviour (demonstrating the "zipping" phenomena)

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[5] *The orderly organization of persons through a narrow walkway or bottleneck such that optimum use of space is achieved by organizing person spatial position in a zip-like fashion (Hoogendoorn, Daamen & Bovy, 2003 and Daamen, 2004)*

Both graphs show the linear relationship between the turnstile gate gap width and pedestrian throughput for gaps greater than 0.45 m. In VISSIM, no pedestrians can pass through a gap of less than 0.4 m.

ASSESSMENT OF TURNSTILE OPERATIONS

Assessment Criteria

The queuing space-density level-of-service (LOS) observed upstream of the turnstiles is currently considered the most appropriate criteria towards the assessment of turnstile requirements.

The queuing space-density level-of-service (LOS) thresholds from the Transit Capacity and Quality of Service Manual (TCQSM[6]), (TRB 1999) indicated in Table 2 are typically used as the default threshold values. These values differ to the thresholds provided in the HCM[7] 2000 (TRB 2000) specifically to account for pedestrian movements within public transit areas (where pedestrians are expected to be in crowded situations) and are therefore typically more conservative than the TCQSM values.

Table 2 – Queuing Space-density LOS Thresholds (TCQSM) (Source: TRB 1999)

LOS	**Queuing Space-density *M* (m^2/pax)**	**Queuing density *k* (pax/m^2)**
A	> 1.2	< 1.1
B	0.9 - 1.2	0.8 – 1.1
C	0.7 - 0.9	1.1 – 1.5
D	0.3 - 0.7	1.5 – 3.0
E	0.2 - 0.3	3.0 – 5.0
F	< 0.2	> 5.0

To determine the required number of turnstiles/access gates necessary to satisfy a certain pedestrian demand (*v*), a queuing LOS C density standard is normally adopted by South African rail authorities with performance requirements as indicated in the table.

Current Methodology

As indicted in the previous section, it is necessary to calculate the queuing densities upstream of turnstiles in order to determine the adequacy of the provided supply (or number) of turnstiles. Traditional methods using textbook formulas for calculating lengths of pedestrian queues at turnstiles are generally not applicable for peaks of short durations where *v*/*c* levels approach and exceed unity (De Neufville and Grillot, 1982).

In order to quantitavely determine the queuing LOS in a case study scenario, the upstream space-density results were accurately calculated using micro simulation modelling methods

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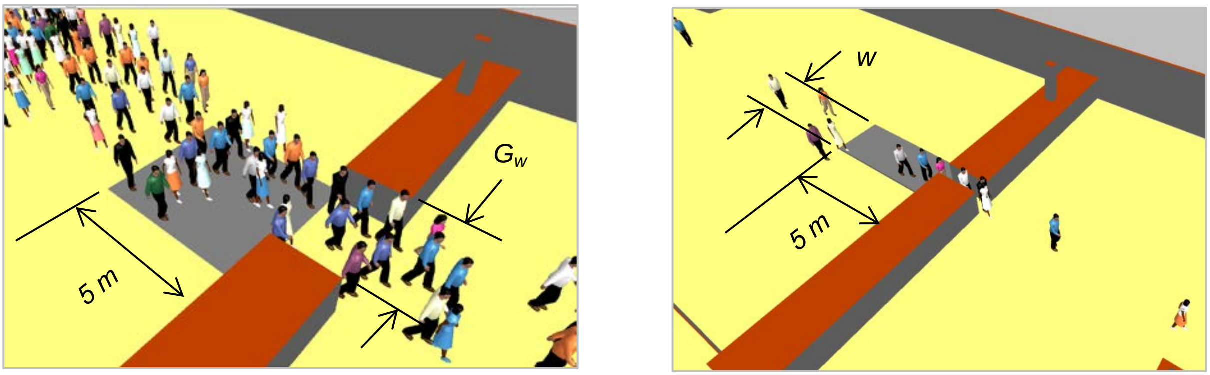
[6] *TCQSM: Transit Capacity and Quality of Service Manual*
[7] *HCM: Highway Capacity Manual*

with measurement area widths that varied (refer to Figures 5(*a.*) and (*b.*) according to a linear relationship with the gap width of the turnstile/access gate[8] (as shown in Figure 6 (*a.*)). In all simulation runs, the depth of measurement areas was fixed at 5.0 m. The measurement area is shown as the grey areas in the figures.

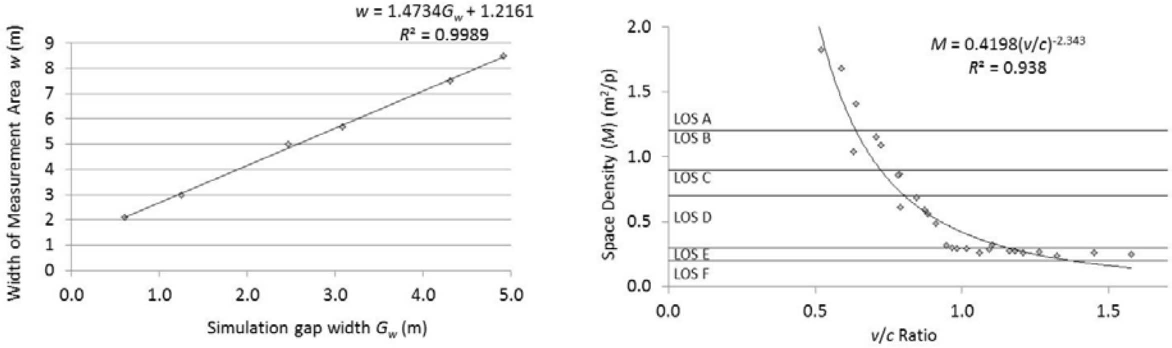
The selection of an appropriate measurement area is important since selection of a large assessment area might yield good queue-density LOS results when in fact queue densities are poor and conversely, calculating densities using a small assessment area upstream of the turnstiles would likely yield consistently poor queue density LOS when in fact queue densities are at acceptable levels.



(a.) Measurement Area for 3.08 m gap (G_w) *(b.) Measurement Area for 0.6 m gap (G_w)*

Figure 5 – Examples of variable measurement area widths (*w*) and Gap widths (G_w)

Through a micro simulation exercise, a volume/capacity (*v*/*c*) versus queue space-density (*M*) relationship profile was developed and plotted (refer to Figure 6 (*b.*)) using modelling analysis techniques. The relationship is considered significant as it provides a simplified method of determining the required number of turnstiles/access gates necessary for a particular demand flow.



(a.) G_w vs. w relationship *(b.) M vs. v/c relationship*

Figure 6 – Turnstile Operational Relationships

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[8] *Based on a standard Passenger Rail Agency of South Africa (PRASA) access gate depth of 1.8 m and 1.2 m height and a modelled male:female gender mix set at a ratio of 2:1.*

From the data collected for this exercise, a simple power relationship is proposed between space-density (M) and the v/c ratio as shown in Figure 6(*b.*) as follows:

$$M = 0.4198 \times (v/c)^{-2.343} \qquad (R^2 = 0.938) \qquad (1)$$

where M is the queuing space-density in m^2/pax, v is the demand in pax/min and c is the turnstile service flow capacity in pax/min.

From this relationship, the following turnstile LOS design bandwidth criteria can be determined:

Table 3 – Turnstile LOS Design Bandwidth Criteria

LOS Design Criteria	***v/c***	***M* (m²/pax)**
LOS A/B	0.64	1.20
LOS B/C	0.72	0.90
LOS C/D	0.80	0.70
LOS D/E	1.15	0.30
LOS E/F	1.37	0.20

This work corroborates with previous preliminary work by the author (Hermant *et al.* 2010) where it was established that the turnstile/access gate operation needs to satisfy a volume/capacity (v/c) ratio of between 0.72 and 0.80 to achieve a reasonable queuing density level-of-service of LOS C.

From the relationship developed in (1), the number of turnstiles (n) required for a particular pedestrian demand volume (v) can then be determined from:

$$M = 0.4198 \times (v/n.c)^{-2.343} \qquad (2)$$

For example, if a LOS C/D turnstile boundary operating condition is required (viz. at M = 0.70), then equation (2) can be written as:

$$1.67 = (v/n.c)^{-2.343}$$

Turnstile Assessment using Average Pedestrian Delay

Whilst the methodology proposed in the previous sections provides a method to calculate turnstile requirements based upon the required upstream queue density LOS, the method can be somewhat misleading since it ignores the queuing (crowding) effect upstream of the turnstiles, especially when the v/c approaches unity and infinite[9] queues develop. The results of a micro simulation exercise shows that infinite queues develop when v/c values exceed 0.92 as shown in Figure 7(*a.*).

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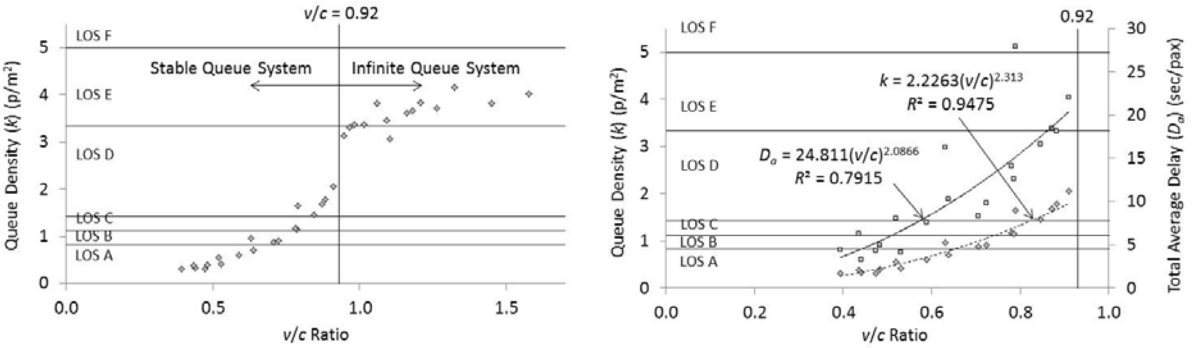
[9] *Infinite queues refers to a queuing system where the arrival demand cannot be serviced by the service facility, resulting in ever increasing queuing.*



(a.) Queue system operational range *(b.) Density and Delay vs. v/c relationship*

Figure 7– Queue limitations and Density/Delay relationships at turnstiles

This paper proposes to introduce total average delay per pedestrian as a turnstile performance criteria (which is considered more pragmatic and in line with other engineering delay-related calculations) instead of a queue density criteria which is perhaps more unfamiliar to general engineering practitioners.

Figure 7(*b.*) shows the relationship between *v/c* and the queue density parameter (*k* represented as pax/m^2) and total average delay (D_a, represented as sec/pax). From Figure 7(*b.*), it becomes possible to associate an average delay (D_a) with each particular LOS design criteria. From the micro simulation exercise undertaken, it was observed that when *v/c* values exceeded 0.92, that LOS D (or worse) queuing conditions and infinite queues developed. The following table provides the associated average delay criteria for each of the LOS boundaries (based on the TCQSM queue density LOS criteria (TRB, 1999)).

Table 4 – Average Delay per LOS Boundary

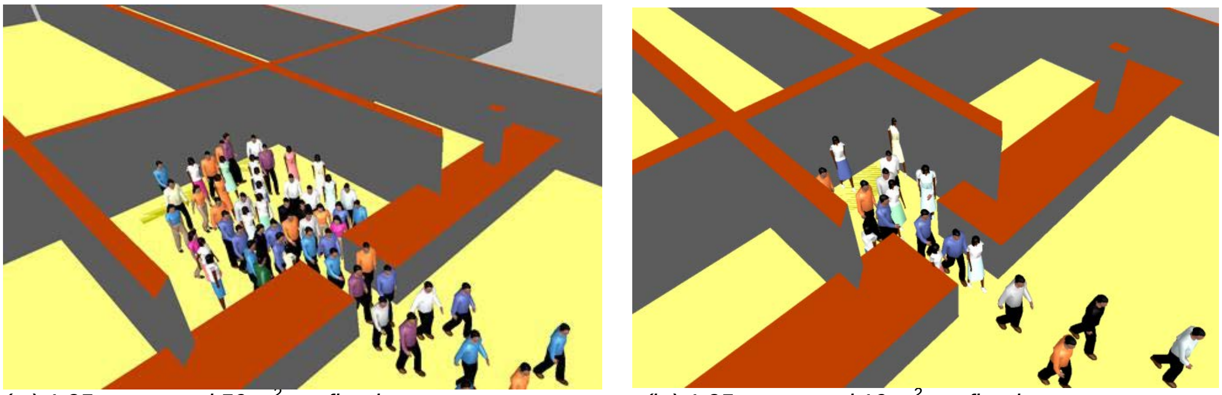
LOS Design Criteria	***v/c***	***k* (m^2/pax)***	**Average Delay D_a (sec/pax)**	***Queue Behaviour***
LOS A/B	0.64	0.83	10.19	Stable
LOS B/C	0.72	1.11	13.24	
LOS C/D	0.80	1.43	16.63	
LOS D/E	*1.15*	*3.33*	*35.68*	*Infinite (v/c > 0.92)*
LOS E/F	*1.37*	*5.00*	*51.48*	

** fixed queue density as per TCQSM criteria*

Spatial Requirements Upstream of Turnstiles

Although the methodology proposed above gives an indication of anticipated average time delay for passengers to pass through a turnstile battery, it does not provide any indication of the space requirements upstream of the turnstiles to accommodate any queuing or crowding effects that may take place. This section provides a method to evaluate this requirement based on micro simulation experiments undertaken in this regard.

The micro simulation exercise involved running iterative scenarios of various confined upstream measurement areas at various *v/c* ratios and plotting the resulting queue density observed covering these areas. Figure 8(*a.*) and (*b.*) shows two such scenarios for a 50 m^2 and 10 m^2 confined upstream space respectively.

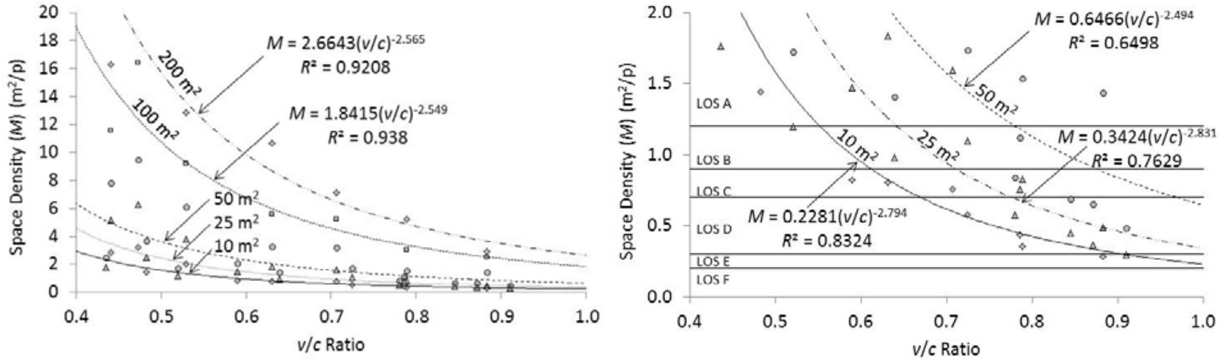


(a.) 1.25 m gap and 50 m^2 confined space

(b.) 1.25 m gap and 10 m^2 confined space

Figure 8– Confined Spatial Areas upstream of Turnstiles

Figure 9(*a.*) shows the results of the micro simulation exercise for 10, 25, 50, 100 and 200 m^2 confined upstream spaces. Figure 9(*b.*) shows the results for the range *M* < 2.0 m^2 indicating the space-density LOS bandwidths.



(a.) M vs. v/c (0 < M < 20 m^2/pax)

(b.) M vs. v/c (0 < M < 2.0 m^2/pax)

Figure 9 – Relationship between *M* and *v/c* for various upstream spaces

From the relationship shown in Figure 9(*b.*), it becomes possible to tabulate the *v/c* values for each of the queue space-density (*M*) LOS bands as indicated in the table below:

Table 5 – Upstream Turnstile Spatial Requirements per LOS Boundary

LOS Design Criteria	***M* (m^2/pax)**	***v/c***		
		10 m^2	**25 m^2**	**50 m^2**
LOS A/B	1.2	0.55	0.64	0.78
LOS B/C	0.9	0.61	0.71	0.88
LOS C/D	0.7	0.67	0.78	0.97*
LOS D/E	0.3	0.91	1.05*	1.36*

** v/c > 0.92 (infinite queues)*

The table can be used to accurately determine minimum upstream spatial requirements for defined operational LOS criteria. For example, assuming that a LOS C/D operational criteria is necessary requiring a *v/c* of 0.8 as per Table 4, then, according to Table 5 above, an unobstructed space of just over 25 m^2 will be required to accommodate any queuing (crowding) effects upstream of the turnstile battery.

Readers are however to be aware that the table does not override the minimum *v/c* requirements recommended in Table 4. In other words, increasing the upstream space from 25 m^2 to 50 m^2 for the situation described above (viz. for a $v/c = 0.8$) will not improve the turnstile operational LOS from C/D to B/C, but rather gives an indication of the crowding density for the given upstream space. Users of the table are therefore cautioned to use the table only to determine upstream spatial requirements.

CONCLUSIONS AND RECOMMENDATIONS

The research undertaken in this paper has contributed towards developing a methodology for determining the number of turnstiles using a more simplified queue density vs. *v/c* power relationship and also proposes using associated average person delays as an alternate method to determine turnstile requirements. The research has also identified that infinite queues begin to develop when *v/c* ratios exceed 0.92.

The important aspect of spatial requirements upstream of turnstiles (to accommodate turnstile queuing) has also been addressed in this paper and space-density (*M*) vs. *v/c* relationships for five floor areas (viz. 10, 25, 50, 100 and 200 m^2) have been used as assessment benchmarks.

It must however be stressed that no calibration or validation of the observed modelled LOS results described in this paper has been done with empirical field surveys, and is a shortcoming requiring further research.

Note that the “gap” method has been applied to uni-directional pedestrian movement only. Further research using micro simulation modeling towards the determination of turnstile requirements for various counterflow ratios should be undertaken.

ACKNOWLEDGEMENT

The author would like to thank Mr. M. Soper for preparing the results presented in certain sections of this paper, particularly with reference to the gap sizing graphics.

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