

Apples and Oranges: Exploring the Effects of Composition on Pedestrian Flow

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Abstract

In recent years, there has been a growing interest in understanding traveller behaviour of pedestrians who form the largest single road-user group. Most individual trips whatever the primary mode used, begin and/or finish with a walk section, so that walking is a fundamental component of all travel. Walking behaviour and pedestrian flow characteristics lay the foundation for the planning and design of pedestrian facilities. This paper explores the effects of pedestrian composition on flow. With major demographic changes facing Australia and most developed countries, established pedestrian evaluation criteria might need revisiting to reflect the current population. Future population demographic is explored based on present trends in population based on the aforementioned changes. A micro-simulation approach is employed in order to investigate the potential effects of increased elderly proportion in pedestrian flow and on the level-of-service (LOS) criteria used in planning and design of pedestrian-dominated facilities. Simulation results show that increased proportion of elderly in pedestrian flow has the potential to shift LOS to a lower level. A shift from LOS B to C, C to D, and D to E are notable for the high elderly proportions.

Keywords: pedestrian flow modelling, ageing population, demographic effects, VISSIM

1. Introduction

Pedestrian traffic does not always consist of a uniform set of pedestrians. This is becoming more evident in the population of developed countries as a consequence of the *ageing population* (OECD, 2001) and the *obesity epidemic* (Pauls, 2008). The Organization for Economic Cooperation and Development (OECD, 2001) estimates that by 2030, one in every four people in the western world will be 65 years or older. Correspondingly, an increase in the number of elderly pedestrians using pedestrian facilities is also anticipated.

If only a small proportion elderly are present within the traffic stream, their effects on flow is small and is normally neglected. Conversely, high proportions will likely have some significant effects. Attempts in considering the effect of heterogeneity in pedestrian traffic has already been presented by several researches. The Highway Capacity Manual (TRB, 2000) suggests a design crossing walking speed of 1.2 m/s if only 0 to 20 percent of pedestrians are elderly, while 1.0 m/s is recommended for percentage more than 20 percent. Teknomo (2002) in his theoretical experiments found that the average speed of the system decreased logarithmically as the percentage of elderly pedestrian increases. Pauls (2008) goes even further by suggesting to consider increasing sidewalk and passageway widths

accommodating enlarged lateral dimensions and sway behaviour caused by slow movement speeds of the elderly and the obese.

Contemporary pedestrian capacity analysis does not implicitly take into account the effect of the heterogeneity in the pedestrian traffic. Unlike vehicular traffic where traffic composition is normalized by the passenger car equivalent (PCE), pedestrian traffic analysis has yet to mature to a level where heterogeneity is incorporated in capacity analysis.

Micro-simulation of pedestrian traffic offers an innovative approach to evaluating hypothetical pedestrian situations. The use of micro-simulation in pedestrian traffic analysis has in recent years become a widely accepted methodology because it allows for the introduction of a much greater number and variety of influencing factors. Despite increasing in popularity, guidelines on the limitations and use of micro-simulation pedestrian models (MSPMs) are yet to be established and standardized. For this study, VISSIM with the Pedestrian Simulation Module was employed to evaluate the effects of elderly proportion on flow.

This paper is organized as follows. The next section briefly discusses literatures in pedestrian modelling and past efforts in modelling heterogeneous pedestrian traffic. The simulation experiment is then described, followed by the analysis of the results and lastly conclusions.

2. Background

The effect of pedestrian composition on flow can be visualized by illustrating a section of walkway wherein pedestrians having the same characteristics are walking compared to the same section with different pedestrian mix. With homogeneous pedestrians (e.g. commuters), pedestrian space tolerance and walking speed is more uniform resulting in better pedestrian flow through the walkway. On the other hand, with non-homogeneous pedestrians (e.g. commuters, elderly, and obese walking together) having different space tolerance and walking speeds, flow will be changed. Specifically, pedestrians requiring greater space when walking and slower-moving pedestrians will contribute to flow reduction. On the whole, the proportion of these pedestrian types will have an effect on the pedestrian flow.

A homogeneous pedestrian stream makes many calculations much simpler because body sizes, walking speeds, and spacing can be held constant. This allows for changes in other variables without the worry of confounding. Heterogeneous pedestrian mixes do not provide this luxury, with a variety of pedestrians interacting with the traffic stream.

The dividing line between homogeneous and heterogeneous pedestrian traffic is not clear cut. Do a few students travelling amongst a stream of commuters cause it to be categorized as heterogeneous? Does one elderly person affect the mix significantly, or is there a certain level up to which the effect of the elderly is not felt? Only a few studies (TRB, 2000) have recommended a cut-off for which it cannot be assumed to operate homogeneously. Pheasant and Haslegrave (2006) recommends a cut off of 30% for any significant effect to be felt.

2.1 Pedestrian Modelling

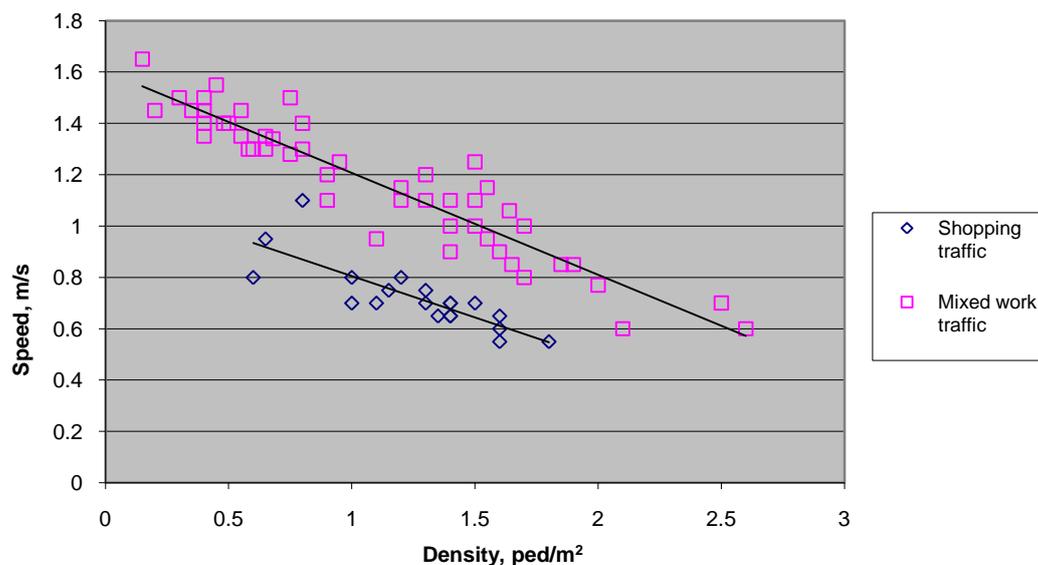
Although pedestrian traffic has been empirically studied for the past 40 years, most of the transportation-related researches still focused on vehicle traffic. Pedestrian flow studies were scarce. With the construction of pedestrian-dominated facilities, such as elevated or underground walkways, stairs and escalators etc., there is an apparent deficiency of pedestrian flow researches for planning and design of those facilities catering to local pedestrian traffic characteristics. Probably the earliest and most widely used approach to quantifying the comfort and safety of pedestrian facilities was the level-of-service (LOS) concept of Fruin (1971). Some of the more

popular approaches to modelling pedestrians include the fluid dynamic analogy by Henderson (1971) and Hughes (2002), gas-kinetic model by Helbing (1998), social force model by Helbing and Molnar (1995), cellular automata (CA) employed by Blue and Adler (1998) and Fukui and Ishibashi (1999), agent-based modelling (ABM) by Schelhorn et al. (1999), Teknomo and Gerilla (2005) and Klugl and Rindsfuser (2007), queuing model by Lovas (1994), and discrete choice model by Antonini (2005).

2.2 Differences in Pedestrian Types

In his study of public footpaths in Germany, Oeding (1963) observed speed and density for different pedestrian facilities locations namely: shopping street, footpath along company buildings, from sport stadium, and close to factory entrances. It can be noticed in Figure 1 that shopping traffic are significantly slower and less dense compared to mixed work traffic. This can be explained by the nature of shopping traffic are being relaxed. In addition, the surveyed shopping traffic consists of larger proportions of older people (mainly women) and children. Meanwhile, mixed work traffic (consisted of workers) walking speed were higher and more spread over the density spectrum. If regression equations are fitted on the speed-density plots of the abovementioned pedestrian traffic, a significant disparity is evident. The projected free-flow walking speed and jam density of shoppers are also significantly lower in comparison to work traffic.

Figure 1. Speed-density plot of shopping and work traffic (Source: Oeding, 1963)



Although Navin and Wheeler (1969) compared different walkway widths in sidewalks at the University of Missouri and Stephens College, different pedestrian types also contributed to the varied walking speeds observed. Traffic from Stephen College was solely female high school students while University of Missouri traffic was mixed and more mature students. Similarly, a significant disparity (see Figure 2) exists between the two types of pedestrians observed.

In addition to the above evidence, Table 1 suggests the diversity of minimum pedestrian area module (PAM), the inverse of pedestrian jam density. Pilgrims tolerate extremely low pedestrian area of up to 0.10 m² (10 pedestrians occupying a 1m x 1m). Shoppers, on the other hand, allow only between 0.242 and 0.286 m²/ped (approximately 4 pedestrians in a 1m x 1m area). Although not all pedestrian types

are covered in this literature, it is assumed that the subject pedestrian types will necessitate different minimum pedestrian area modules.

Figure 2. Speed-density plot of high school and university students (Source: Navin and Wheeler, 1969)

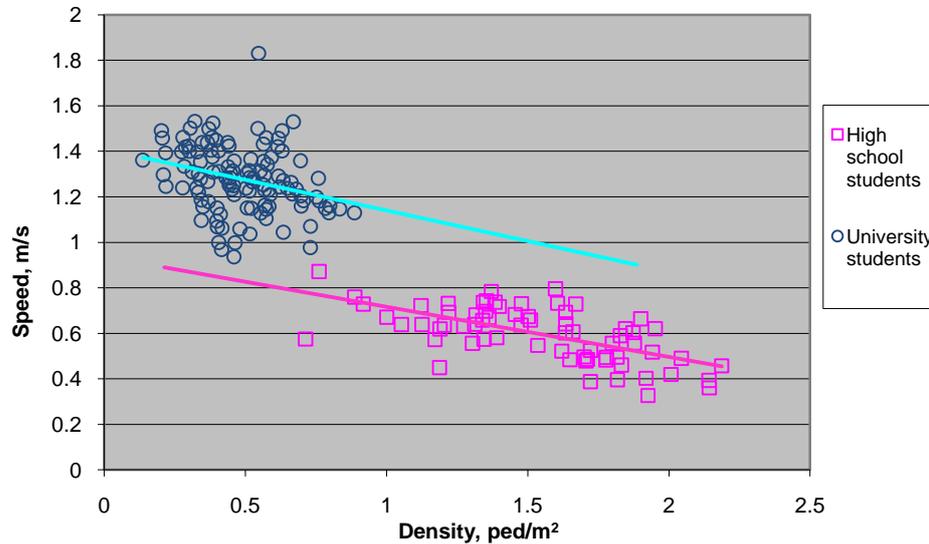


Table 1. Minimum pedestrian area module by pedestrian type

Source	Type of Pedestrian	Min PAM, M_{jam} (m ² /ped)
Hankin & Wright (1958)	Commuter	0.187
	School boys	0.155
Oeding (1963)	Shoppers	0.286
	Mixed traffic	0.247
Older (1968)	Shoppers	0.242
Navin & Wheeler (1969)	Female secondary students	0.235
	Mixed university students	0.191
Mori & Tsukaguchi (1987)	Commuters	0.155
Seyfried et al. (2005)	University students & staff	0.484 ¹
Helbing et al. (2007)	Pilgrims	0.101

Note: ¹ Unit is in m/ped and set-up used was experimental

2.3 Modelling Pedestrian Composition

Because of the diversity of traveller compositions according to Ye et al (2008), traffic flow characteristics are site and region specific. How to design effective and reasonable pedestrian facilities complying with local pedestrian characteristics and composition is essential in densely populated pedestrian facilities, which is typical of rail transit stations. Based on the early efforts, studies put emphasis on the differences of pedestrian flow characteristics for different countries resulting from the inherent dissimilarity of body feature and national culture (Chattaraj et al., 2009). Although extensive research has been done over the years regarding pedestrian flow in transport facilities, few studies (Hughes, 2002, Lovas, 1994) have considered pedestrian composition in pedestrian flow.

An attempt in considering the effect of heterogeneity in pedestrian traffic was suggested by the Highway Capacity Manual (TRB, 2000) wherein if 0 to 20 percent of pedestrians are elderly, a design walking speed of 1.2 m/s is recommended while

1.0 m/s for percentage more than 20 percent. Teknomo (2002) in his theoretical experiments found that the average speed of the system decreased logarithmically as the percentage of elderly pedestrian increases. Pauls (2008) goes further by suggesting considering increasing sidewalk and passageway widths to accommodate enlarged lateral dimensions and sway behaviour caused by slow movement speeds of the elderly and obese.

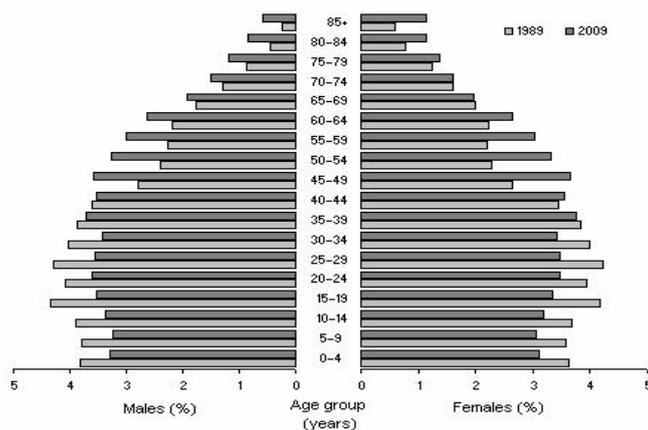
Lovas (1994) suggested dividing all factors influencing walking speed in two groups: personal factors and situational factors. The personal factors are the inherent characteristics of the said pedestrian group and described by the mean and standard deviation of the group. The situational factors will be more or less constant for the whole population (e.g. the temperature is the same, the trip purposes are not too different, etc.). Hughes (2002) in his hydrodynamic model derived governing flow equations for multiple pedestrian types.

2.4 Australia's Ageing Population

Populations of almost all developed countries are ageing. According to the Australian Bureau of Statistics (ABS, 2009), the elderly comprise the fastest growing segment of the population. This is in agreement with a publication on ageing and transport by the OECD (2001) stating that the gradual rise in the proportion of older people is expected to intensify so that by 2030, one in every four people in the western world will be 65 years or older. And 'by 2030, the number of people aged 80 or more will have doubled and by 2050, it will have tripled' (2001, p. 17).

ABS (2009) further detailed that in Australia, the proportion of the population aged 65 years and over increased from 11% to 13.3% between 1989 and 2009 (illustrated in Figure 3). This proportion is projected to increase to 19.6% of the total population in 2030 (2009). With this drastic change in the composition of the population, Coughlin (2001, p. 2) suggested that there is a 'need to understand how this cohort gets around in order to successfully design programs to help them overcome barriers of mobility'. Because of the growing proportion of this group in the population, understanding their travel preferences can aid in developing policies for planning pedestrian facilities.

Figure 3. Australia's population structure – 1989 and 2009 (Source: ABS, 2009)



3. Pedestrian Micro-simulation

Micro-simulation of pedestrian traffic offers an innovative approach to evaluating hypothetical pedestrian situations (Galiza et al., 2009). The use of micro-simulation in pedestrian traffic analysis has in recent years become a widely accepted methodology because it allows for the introduction of a much greater

number and variety of influencing factors. VISSIM has been employed here to evaluate the effects of pedestrian composition particularly the increase in proportion of elderly in the traffic stream. The pedestrian choice model behind VISSIM is called the “*Social Force Model*”. The mathematical algorithm for this model was first published by Helbing and Molnar (1995) and since then been enhanced and validated by other researchers (Lakoba et al., 2005, Quinn et al., 2003, Wei-Guo et al., 2006). This model is both flexible and robust that it could model even extremely congested conditions (Helbing et al., 2007) compared to other pedestrian simulation models. Other popular pedestrian micro-simulation models include SimWalk® (Savannah Simulations), Legion® (Legion Studio), MicroPedsim® (Teknomo, 2006) and NoMad® (Delft University of Technology).

3.1 VISSIM’s Social Force Model

The Social Force Model was designed to represent the stochastic behavioural models of pedestrian movements. Based on Newtonian ideas, the interaction of pedestrians considers a number of different forces to minimise journey time and reduce the overall number of conflicts to inhibit flow. Each identified category of pedestrians can be associated with different desired speed and characteristics to simulate the variation attributable to demographic attributes (PTV, 2009).

3.2 Simulation Set-up

A flat walkway test bed was considered for the simulation set up. The walkway measured 10 meters by 1.5 meters. The type of flow considered initially for this experiment is unidirectional. In order to define the geometry of the walkway set up, the network editing module for pedestrians of VISSIM was employed and the geometry of the walking areas were specified. The characteristics of the different pedestrian types were defined and the inputs and routes of pedestrians were added to the geometry.

3.3 Model Input

The source of data for the model was mainly from Table 2 which describes the different LOS for walkways. This table also details the corresponding pedestrian space, average speed, flow rates, and volume-capacity ratio for the different LOS. Mid-value flow rates were used as input to the simulation models while the corresponding mid-value pedestrian space and average speed were used for model calibration. The decision to utilise Fruin’s (1987 as cited in Kittelson and Associates, 2003, p. 7-11) data found in the *Transit Capacity and Quality of Service Manual (TCQSM)* also serves as a basis for evaluating the effect of pedestrian composition on LOS.

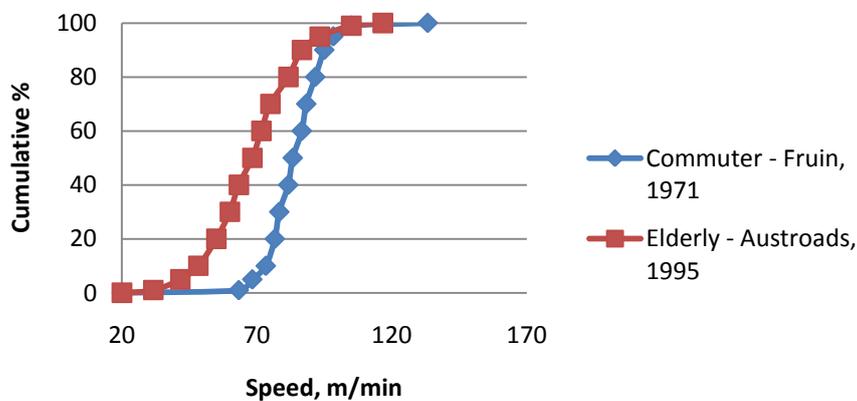
Table 2. Pedestrian LOS for walkways (Fruin, 1987 as cited in Kittelson and Associates, 2003, p. 7-11)

LOS	Pedestrian Space (m ² /p)	Expected Flows and Speeds		
		Avg. Speed, <i>S</i> (m/min)	Flow per Unit Width, <i>v</i> (p/m/min)	<i>v/c</i>
A	≥ 3.3	79	0-23	0.0-0.3
B	2.3-3.3	76	23-33	0.3-0.4
C	1.4-2.3	73	33-49	0.4-0.6
D	0.9-1.4	69	49-66	0.6-0.8
E	0.5-0.9	46	66-82	0.8-1.0
F	< 0.5	< 46	Variable	Variable

v/c = volume-to-capacity ratio

One of the main issues when considering pedestrian composition in analysing flow is whether microscopic characteristics should be gathered separately for the different pedestrian types or combined to form a single group taking note of the proportion of the other groups. To consider the effects of pedestrian composition, the former is the more appropriate pedestrian type characteristics as the proportion can easily be changed for the different simulation models. There are two types of pedestrian considered for the simulation models: commuters and the elderly. The two most important VISSIM input characteristics for the two pedestrian types are the body size and walking speed distributions. The walking speed distribution for commuters and the elderly were assumed to conform to values found by Fruin (1971) and Austroads (1995), respectively as shown in Figure 4. According to Buchmueller and Weidmann (2006), pedestrian body sizes for the average pedestrian and the elderly are very similar. Thus, the same 3-D pedestrian models were used for both types.

Figure 4. Walking speed distribution for commuters (Fruin, 1971) and elderly (Austroads, 1995)



The flow rate per unit width used for the models were mid-values of the range defined by Fruin (1987 as cited in Kittelson and Associates, 2003, p. 7-11) as shown in Table 3. In this way, the model results (pedestrian space and average speed) can be compared with the average values from the same reference.

Table 3. Flow rate model input (ped/m/min)

	LOS A	LOS B	LOS C	LOS D	LOS E
Fruin (1987) Low	0	23	33	49	66
Model	12	28	41	57	74
Fruin (1987) High	23	33	49	66	82

In order to distinguish between flows associated with the LOS and flows used in the simulation models, the mid-value unit flow rate for LOS A will be referred to as Flow A (12 ped/m/min). While, the mid-value unit flow rate for LOS B, LOS C, LOS D, and LOS E corresponds to Flow B (28 ped/m/min), Flow C (41 ped/m/min), Flow D (57 ped/m/min), and Flow E (74 ped/m/min), respectively.

4. Results and Discussion

4.1 Model Calibration

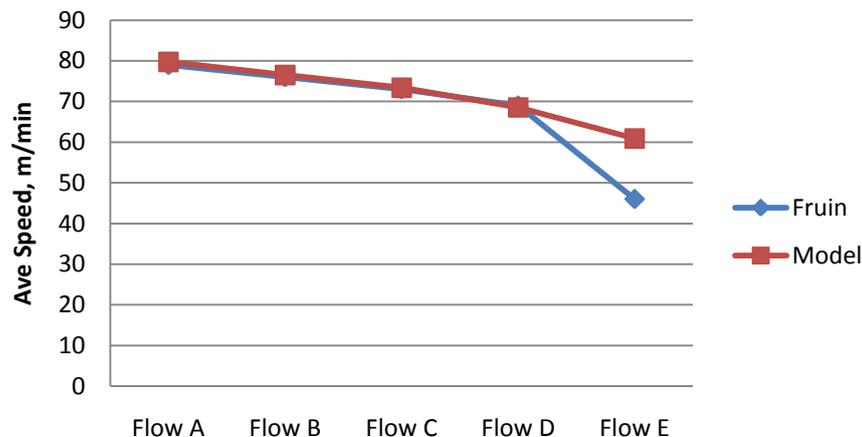
In order to calibrate the walkway simulation set-up (10m by 1.5m), mid-value flow rates were inputted to the base model comprising of 100% commuters with the walking speed profile by Fruin and comparison were made with the corresponding pedestrian space values from the simulation runs. Table 4 shows the pedestrian space for each flow obtained for the model is well within the range defined by Fruin.

Table 4. Pedestrian space from simulation model versus Fruin (m²/ped)

	Flow A	Flow B	Flow C	Flow D	Flow E
Fruin Low	3.3	2.3	1.4	0.9	0.5
Model	6.8	2.8	1.8	1.2	0.8
Fruin High	-	3.3	2.3	1.4	0.9

The values of the average walking speeds for the simulation models and Fruin's (1987 as cited in Kittelson and Associates, 2003, p. 7-11) are illustrated in Figure 5. For all flows up to level D, the simulation model results are very close to Fruin's. For flow E, where very congested conditions apply, the model overestimates average speeds by 25%.

Figure 5. Average walking speed from the simulation models and Fruin's



4.2 Model Results

The simulation results for pedestrian flow rate and walking speed as a function of pedestrian space were compared with those obtained using Fruin's. Figure 6 shows the effect of increasing the proportion of elderly on flow rate and average pedestrian space. For the same flow rates, average pedestrian space decreases with a corresponding increase in the proportion of elderly traffic. The graph of the flow rate versus pedestrian space shifts to the left as the proportion of elderly pedestrians increase. Table 5 shows the percentage reduction in pedestrian space for different elderly proportions. For low flow conditions, average pedestrian space reductions were less significant compared with high flow conditions. For the predicted proportion of elderly Australians by 2030 (20% of the population), a 7.0% reduction is predicted for low flow condition (Flow A) while 40.0% for Flow E in comparison to the baseline Fruin simulation models.

Figure 6. Pedestrian flow versus space for different proportions of elderly

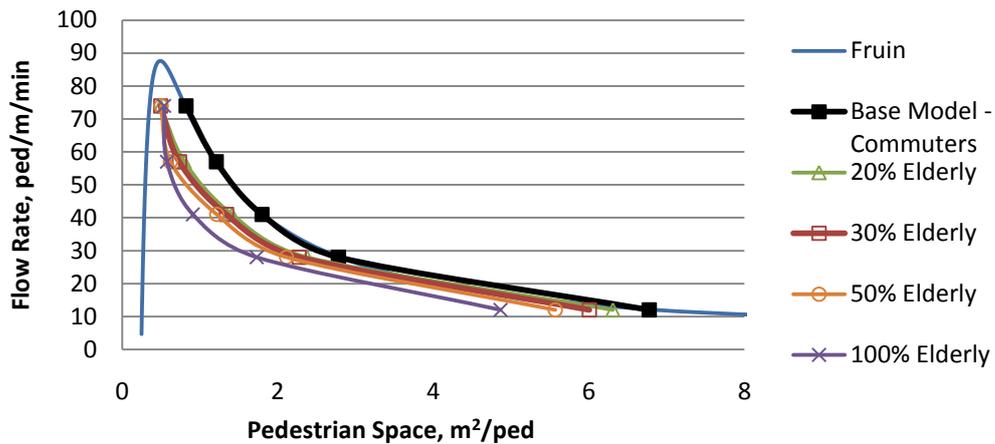


Table 5. Average pedestrian space reduction (%) for different proportions of elderly in relation to calibrated Fruin simulation model

% Elderly	20%	30%	50%	100%
Flow A	-7.0	-11.4	-14.8	-28.3
Flow B	-14.5	-18.1	-21.3	-37.8
Flow C	-21.5	-25.5	-29.4	-49.5
Flow D	-33.9	-39.1	-45.0	-52.6
Flow E	-40.0	-39.7	-39.6	-34.4

Figure 7 shows the effects of increasing the proportion of elderly on both average speed and pedestrian space. Table 6 shows the percentage reduction in average speed for different elderly proportions. Similar to pedestrian space, under low flow conditions and low proportion of elderly, average speed reductions were less pronounced compared with high flow conditions and high elderly proportions. For the predicted proportion of elderly Australians by 2030 (20% of the population), a 7.2% reduction is predicted for low flow condition (Flow A) while 41.8% for Flow E in comparison to the baseline Fruin simulation models.

Figure 7. Pedestrian speed versus space for different proportions of elderly

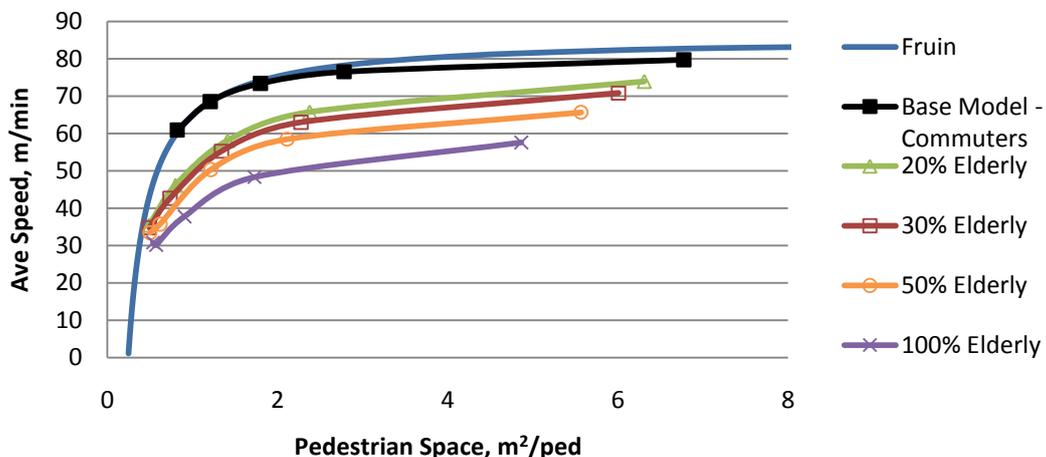


Table 6. Average pedestrian speed reduction (%) for different proportions of elderly

% Elderly	20%	30%	50%	100%
Flow A	-7.24	-11.18	-17.64	-27.76
Flow B	-14.04	-17.68	-23.57	-36.86
Flow C	-20.80	-24.75	-31.47	-48.52
Flow D	-32.66	-37.80	-47.85	-55.97
Flow E	-41.76	-42.90	-45.13	-49.43

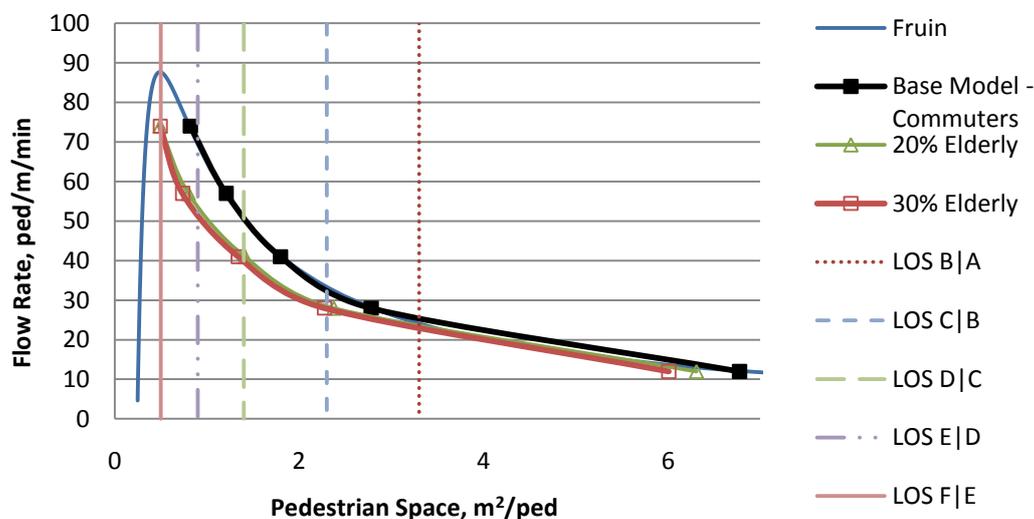
5. Conclusions

A micro-simulation approach was employed to investigate the potential effects of increased elderly proportion in pedestrian flow and on the level-of-service (LOS) criteria used in planning and design of pedestrian-dominated facilities. Simulation is a powerful tool for evaluating theoretical pedestrian scenarios. As the proportion of elderly pedestrian increases, average pedestrian space and average speed decreases for corresponding pedestrian flow rates. Under low flow conditions, its effect on average pedestrian speeds for low proportion of elderly is less pronounced. Speed reductions are significantly higher for high flow rates and high proportions of elderly.

The most important contribution of this simulation methodology is to be able to examine the possible repercussion of increased proportion of elderly in pedestrian flow. As can be observed in Figure 8, under medium to high flow conditions, high elderly proportion can shift the LOS to a lower level. A shift from LOS B to C, from C to D or D to E is of particular interest as these LOS' (B to D) are generally used in designing pedestrian facilities. A misrepresentation of the desired LOS might result in increased elderly proportion.

The effects of other pedestrian types may also be explored using the same methodology. Their proportion in certain situations may actually be significant in order to merit this analysis presented here. These special situations include pedestrian facilities located near pedestrian generating/attracting facilities like airports (tourists), schools (students), retirement facilities (elderly), etc. The procedure employed in this paper can also be applied to evaluate the effects of other pedestrian types during emergency situations.

Figure 8. Effect of elderly proportion on LOS for narrow walkways



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VISSIM®, SimWalk®, Legion®, MicroPedsim® and NoMad® are registered trademarks of PTV AG, Savannah Simulations, Legion Studio, Teknomo(2006) and Delft University of Technology, respectively.

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