School of the Built Environment
Napier University

FACTORS AFFECTING PEDESTRIAN WALKING SPEEDS

MARWAN AL-AZZAWI

A thesis submitted in partial fulfilment of the requirements of Napier University for the degree of **Doctor of Philosophy**

October 2004

ABSTRACT

The movement of pedestrians in the urban environment is vital for sustaining the social and economic relationships essential to the quality of life. To enable and encourage walking, suitable facilities must be available and planning and implementing such facilities requires an understanding of the characteristics of pedestrian movements. This thesis examined the factors which influence walking speeds, related them to current pedestrian modelling techniques and developed a series of new models to improve their estimation. A comprehensive review of current practices and procedures for modelling pedestrian walking speeds was carried out, identifying the factors currently used in existing methodology and highlighted its deficiencies. A significant finding from this study was that the industry-standard Highway Capacity Manual (HCM) methodology as it currently stands is not fully applicable to the types of walking environments that were the subject of this research (on-street walkways in UK shopping and Central Business District areas). It was shown there is a need to provide more holistic relationships which take into account the interactions between the characteristics of pedestrians and their walking environments (both built and natural). A number of additional factors which have a significant affect on walking speeds were identified and a series of new statistical relationships were developed which were also tested and validated against independent data. The predictive performance of the new models was also compared against the leading industry-standard methodology and shown to provide significantly better estimates. Future areas of research were also identified and described.

The research thus provided a greater understanding of the dynamics affecting walking speeds, thereby helping to assist transport planners and engineers with the study and design of suitable pedestrian facilities.

DECLARATION

I declare that this thesis was composed
by myself and that the work it describes is my own
unless otherwise stated.

Marwan AL-Azzawi, October 2004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to thank my two supervisors, Mr Derek Barker and Dr Robert Raeside, for their support and guidance throughout the period of this research.

I would also like to thank all those organisations and companies, too many to name individually, who assisted in providing information and data without which this research would not have been possible.

Finally, a big thank you to Miss Jenny Whyte for her assistance during the final stages of the research and my family for their support throughout my education.

1 INTRODUCTION

1.1 Background

The movement of pedestrians in the urban environment is vital for sustaining the social and economic relationships essential to the quality of life. Walking enables individuals to have direct contact with the environment and other people, enables the passage of people from place to place, and makes possible the access to areas where vehicular movement is not possible or is not desirable for safety and/or ecological reasons. To enable and encourage walking for different purposes, the physical facilities must be available to support the physiological, psychological and social needs of pedestrians and ensure them against overexertion, interference from other road users and accidents. Planning and implementing such facilities requires an understanding of the characteristics of pedestrian movements.

To assist with the design and construction of pavements, several mathematical models have been created over the years and used in computer simulation packages such as CUBE Voyager (Citilabs, 2002) and PEDROUTE (Halcrow, 2002a). However, before-and-after studies have shown that the predictive powers of these models are very weak, with many calling for a more detailed and thorough set of statistical relationships to use as the building blocks for enhancing the current predictive powers and hence improve the understanding of pedestrian movement and the characteristics of their needs (for example Kaplan et al, 1998; Clifford, 1999; and Hoogendoorn and Bovy, 2002).

1.2 Aims of this Research

There are six main aims for this thesis, namely:

1. review current practices and procedures for modelling pedestrian movements;

2. identify the factors and variables used in current modelling processes and test their goodness-of-fit using independent data;

3. determine other factors which have a significant affect on the walking speeds of pedestrians in certain types of walking environments and conditions;

4. attempt to develop statistical relationships which can be used by transport planners to model the interactions between these factors and walking speeds, and thereby assist transport planners with the study and design of suitable pedestrian facilities;

5. test and validate the statistical relationships developed; and

6. identify and discuss future areas of research.

The intention of this is to provide a greater understanding of the dynamics affecting walking speeds, thereby assisting transport planners and engineers with the study and design of suitable pedestrian facilities.

1.3 About this Thesis

After this introduction, discussed in Chapter Two are the findings of a review of past studies and literature. This describes the key points emerging from the analysis of past and current practices. Summarised in the Chapter are how pedestrian movements are analysed and modelled, and an introduction to the concepts and techniques currently used is provided. Examples of some of the most popular pedestrian computer software models employed with a brief overview of their workings are also described, along with details of what data is typically required to assess pedestrian walking. Findings from previous research, covering a wide range of issues and factors determining the analysis of pedestrian movements, are then set out.

The review of past studies and published literature on pedestrian planning is only part of the picture, in that it does not explain why it is important to have robust means of studying walking movements and designing pedestrian facilities. This is discussed in Chapter Three, which helps set the scene for this research, and demonstrates how important walking is to a well-balanced and sustainable Government transport strategy. Historical trends are reviewed and the effects of different trip types and how they impact on walking behaviour are highlighted. The extent to which the characteristics of the environment can have a significant influence and the role walking has in modern society is also considered.

An initial analysis of walking speeds recorded at a pre-selected site is presented in Chapter Four. Walking speeds, flows, densities and other parameters were recorded to quantify the effects of different factors on pedestrian movements and identify variables which seem to exhibit a significant level of influence. This helped provide an indication of walking speeds and densities for observed levels of flows, and to allow the development of some mathematical relationships between them with a view to providing insights into the various different levels of interactions. An indication of the form and quantity of information needed for a more detailed data collection and analysis exercise is then given.

All the work up to this point in this thesis is aimed at identifying the strengths and weaknesses of current practices, and setting the scene for the rest of this research. It is considered that the findings suggest better predictive models will be required. Consequently a series of Research Hypotheses were developed to test some of the propositions identified earlier. These are pursued in a clear and systematic Research Method set out in Chapter Five.

The data assimilated from various video surveys will be used in Chapter Six to undertake various statistical tests to identify those variables and factors which seem to influence walking speeds and to develop a series of new mathematical models. The Chapter will begin with an overview of the data collected to test the hypotheses and will follow the methodological approach described in Chapter Five. Statistical tests including t-tests, analysis of variance and graphical analysis are then carried out. These tests helped identify the key variables for inclusion in the new models.

The best-fit models and the results of their initial validation are then presented, along with details of their operational ranges. A series of discussions on the findings is then presented. This includes a summary of the results and the categorisation of the variables required to use the new models. The levels of sensitivity of the variables in the new models will also be discussed.

One of the primary objectives of this research will then be to validate the developed models against an independent set of data. Presented in Chapter Seven are the results of the model validation and tests. The Chapter begins by explaining the process used for validation, and the reasons for its selection, before setting out a series of comparisons of estimates from the new models against a series of independent observations. A number of statistical tests will be presented showing the goodness-of-fit of the model's forecasts. The Chapter will then conclude with a discussion on the findings and their implications for pedestrian modelling.

Conclusions based on the findings of this analysis and their implications for pedestrian modelling will be presented in Chapter Eight, along with a discussion on recommendations for future research.

2 PAST STUDIES AND LITERATURE REVIEW

2.1 Introduction

A review of past studies and published literature on pedestrian planning is given in this Chapter. The Chapter begins by summarising how pedestrian movements are analysed and modelled. This includes an introduction to the concepts and techniques currently used, examples of some of the most popular pedestrian models employed with a brief overview of their workings and what data is typically required to assess pedestrian walking. Then set out are the findings from previous research, covering a wide range of issues and factors which determine pedestrian movements. These include the effects of different pedestrian types, how trip purposes are perceived to impact on walking behaviour and the extent to which the characteristics of the environment are believed to have a significant influence. All these are aimed at identifying the strengths and weaknesses of current practices. Consequently, the discussion at the end of this section draws all these strands together and sets the scene for the rest of this research.

2.2 Analysing Pedestrian Movements and Facilities

2.2.1 Background

Pedestrian movements and facilities are analysed using a series of walking comfort and safety indicators, which quantify the Level-of-Service (LOS) experienced by pedestrians as they traverse the area being examined. Fruin (1971) devised the LOS indicator by measuring the flow of pedestrians per unit area of walkway. He then identified six types of LOS indicators, ranging from A (the most free flow of conditions) to F (extremely congested conditions, where progress would be by means of shuffling).

While these LOS indicators are able to give an indication of the relative intensity of movement in an urban setting, they cannot explain the processes which cause them and certainly cannot be used to predict future patterns (Helbing, 1997).

Shortly after Fruin published his work, the Transportation Research Board (TRB), a unit of the National Research Council in the United States, incorporated Fruin's LOS concept in its Highway Capacity Manual (HCM). Over the years, the HCM has been continually updated and reprinted, and is now widely used as the means for obtaining guidance for the study of transportation facilities, including pedestrian analysis. Over the years, the HCM has become the source for most pedestrian LOS variables for use in pedestrian assessments in the UK (Zegeer et al, 1994).

In other countries, others have adapted the theory of Fruin's work and developed their own LOS indicators with a view to taking cognisance of their own local variations. These will be compared later in this Chapter, but firstly an overview of parameters and techniques set out in the HCM will be discussed below.

2.2.2 The Highway Capacity Manual and Similar Guidelines

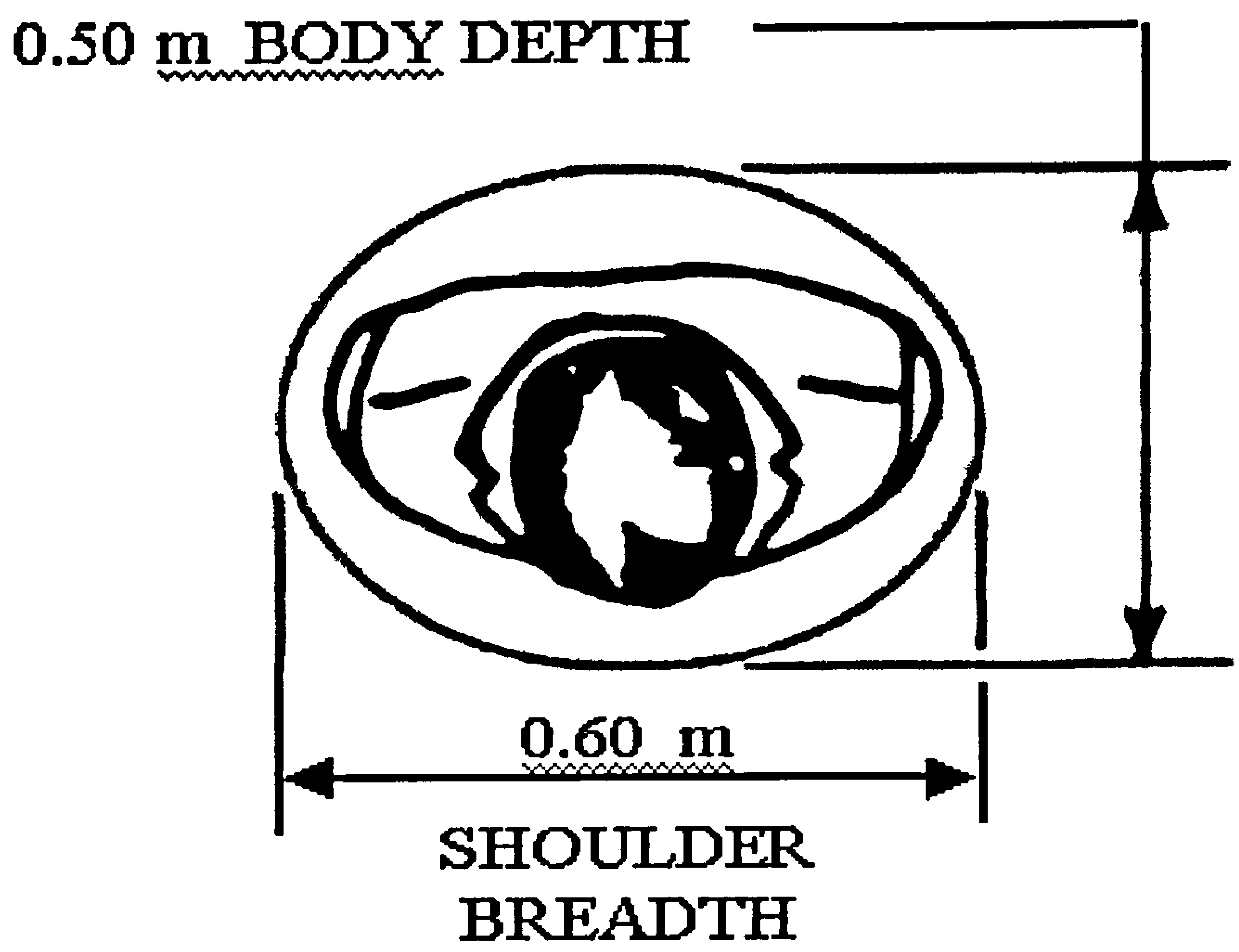
Chapter 13 of the 2000 edition of the HCM (TRB, 2000) discusses the operational and planning analysis of pedestrian facilities. The HCM pedestrian chapter begins by posting some relationships between pedestrian speed, flow and density. It continues with analysis procedures for walkways, street corners and crosswalks.

Although offering the transport planner and engineer the means to analyse the most common pedestrian facilities, Milazzo et al (1999) argued some of the procedures rely on incomplete and outdated information. They agreed this is unfortunate, because many intersections and walkways in urban areas have moderate to heavy pedestrian flows, thus warranting accurate procedures. However, the need for new procedures stems from reasons besides outdated methods, as discussed by Naderi and Raman (2002). They showed that the heightened importance of "livability" in communities presents the transport planner and engineer with the challenge to fully incorporate pedestrians in transportation.

2.2.2.1 Pedestrian Space Requirements

From his research findings, Fruin (1971) introduced the concept of *Body Ellipses and Buffer Zones* and argued that pedestrians strive to keep a certain distance between themselves and other pedestrians. This dictates their level of comfort and influences walking speeds. For design purposes, the HCM sets out a simplified body ellipse of 50 cm x 60 cm for standing areas, with a total area of 0.3 m^2, or roughly 108 percent of the ellipse suggested by Fruin (1971). This shape (Figure 2.1) serves as an approximate metric equivalent to Fruin's ellipse. It also recommends a body buffer zone of 0.75 m^2 for walking, which is near the upper end of the buffer zone range identified by Pushkarev and Zupan (1975a) and which proceeds the onset of "unnatural shuffling".

Figure 2.1: Body Ellipse for Standing Areas recommended in the HCM



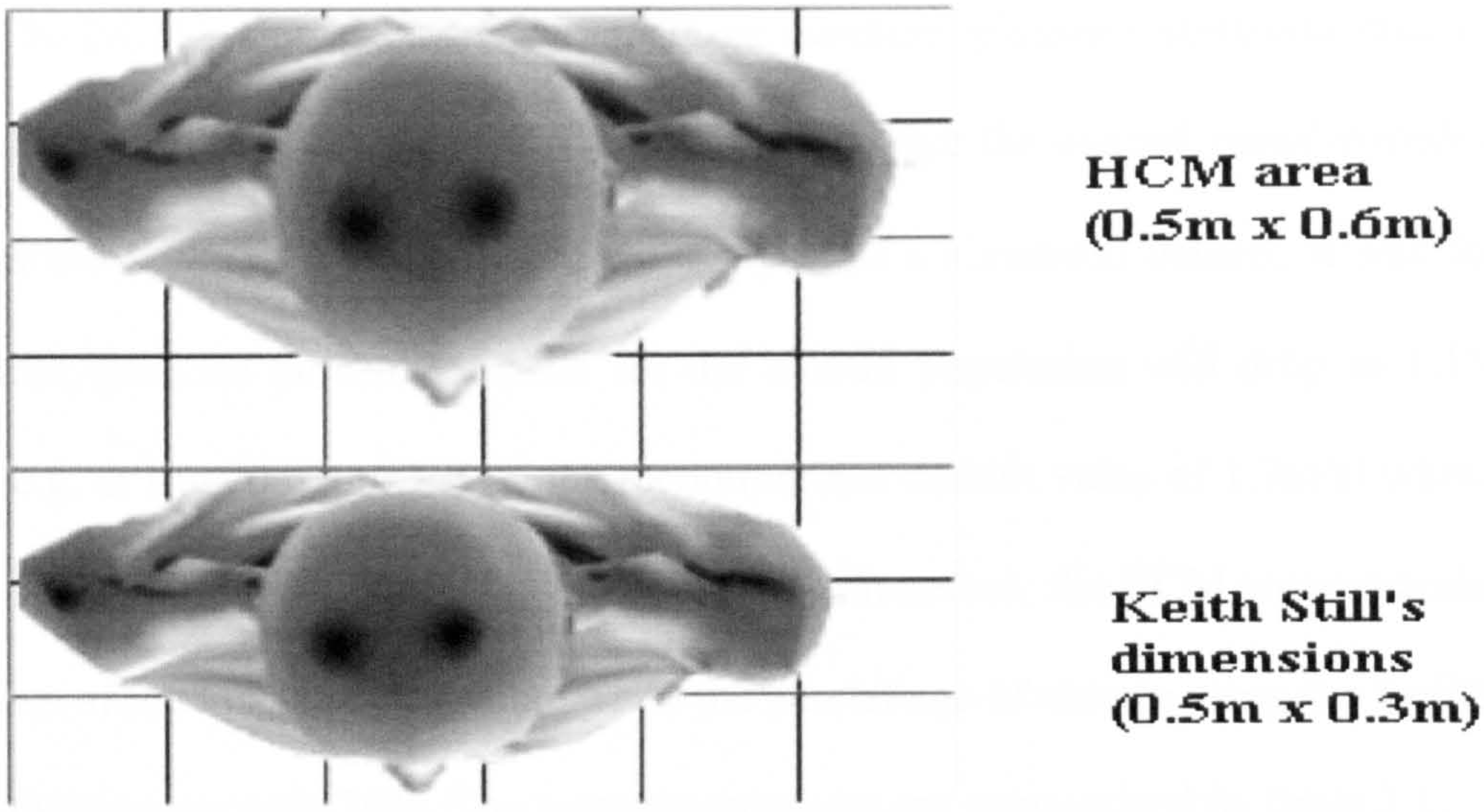
Source: Highway Capacity Manual (TRB, 2000)

It is worth remembering, the dimensions cited in the HCM are 108% times those found by Fruin (1971). Fruin believes the body ellipses and buffer zones are key determinants, as the following paragraph paraphrased from his book shows (Fruin, 1971 - page 19):

> *"Body depth and shoulder breadth are the primary human measurements used in considering pedestrian spaces and facilities. Shoulder breadth is the major factor in the design of doorways, stairways etc. Many portals are designed to allow two or more persons to pass through abreast but actually have insufficient width for this purpose."*

By way of comparing the recommended dimensions against more recent research, Figure 2.2 shows the dimensions of a study by Still (2000) comparing his own body dimensions against the HCM values.

Figure 2.2: Comparison of Body Ellipses



Source: Still (2000)

Still's findings suggest the HCM allocations, which are larger than Fruin's original recommendations, are quite generous, but it is worth noting that the environments Fruin measured and applied his level of service calculations were predominantly city streets.

2.2.2.2 Pedestrian Walking Speeds

Age of Pedestrian

The HCM (TRB, 2000) recommends a pedestrian walkway walking speed value of 1.2m/s (3.9 ft/s) for most conditions. In areas with large numbers of older pedestrians, a walking speed value of 1.0m/s is recommended. This is a near 30% decrease on the previous value.

The question may arise, "*what constitutes large numbers of older pedestrians?*". The HCM's suggested answer is, *"large numbers of older pedestrians exist when the elderly proportion begins to materially affect the overall speed distribution at the facility."* Through a simple analysis of a simulated dataset, it was found that the 15th percentile speed for the overall population will drop to 1.15m/s (e.g. at least 0.05m/s below the recommended default value of 1.2m/s) when the elderly proportion increases to about 20%. Therefore, the HCM recommends the use of the lower 1.0m/s value when the percentage of elderly using the facility in question exceeds 20%. The recommendations are summarised in Table 2.1.

Surprisingly, there appears to be no allowances made for young people.

Table 2.1: Recommended Pedestrian Walking Speeds from HCM

Facility Population above the Age 65	**Suggested Walking Speed[a] for Time-Limited Walkways[b]**		
(% of all facility users)	(m/s)	(ft/s)	(% decrease from 1994 edition of HCM[c])
0-20	1.2	3.9	14%
> 20	1.0	3.3	29%

[a]If necessary, adjust minimum crossing time for platoon flow

[b]Crosswalks and other facilities where available user time is limited

[c]1994 edition of HCM uses 1.4m/s (4.5ft/s) design crosswalk walking speed

Sources: Highway Capacity Manual 2000 Edition (TRB, 2000)
Highway Capacity Manual 1994 Edition (TRB, 1994)

Grades and Stairs

The HCM suggests it is not necessary to correct for grades less than 10%. Above 10% on upgrades, the HCM advocates a 0.1m/s reduction in walking speed as an approximation (roughly the amount found by the Institute of Transportation Engineers in 1976).

Platoons

For most situations where platoons (groups of pedestrians) are prevalent, the HCM does not recommend the use of walking speeds lower than 1.2 m/s (1.0 m/s for large elderly populations). However, when assessing the crossing time required at signalised intersections and in light of the research by Virkler (1996) described in the *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual* (Rouphail et al, 1998), the current edition of the HCM recommends increasing the minimum signalised intersection crossing time when typical platoons exceed 15 people.

2.2.2.3 Pedestrian Facilities and their Measures of Effectiveness (MOE)

Pedestrian Walkway Capacity

Given the buffer zone recommendations described above, the HCM suggests that walkway capacity lies between 4,000 and 5,000 pedestrians/hour/metre. For simplicity, the HCM recommends an assumed capacity of 75 ped/min/metre (4,500 ped/hour/metre) and an assumed speed at capacity of 0.75m/s. These are based on a buffer zone space of 0.75m^2/ped for a capacity threshold.

Sidewalks and Walkways

The current HCM uses pedestrian space as the primary measure of effectiveness (MOE), with mean speed and flow rates as secondary measures (Table 2; TRB, 2000). Carrying units of area per pedestrian in the existing HCM, the measure offers a simple, intuitive method of service evaluation. Defined in this chapter is capacity at 6ft^2/ped (about 0.56m^2/ped).

Table 2.2: HCM Walkway Level of Service (LOS) criteria

LOS	Space		Flow Rate		Average Speed		v/c ratio
	(m^2/ped)	(ft^2/ped)	(ped/min/m)	(ped/min/ft)	(m/s)	(ft/min)	
A	$\geq$5.6	$\geq$60	$\leq$16	$\leq$5	$\geq$1.3	$\geq$255	0.21
B	3.7-5.6	40-60	16-23	7-5	1.27-1.30	250-255	0.21-0.31
C	2.2-3.7	24-40	23-33	10-7	1.22-1.27	240-250	0.31-0.44
D	1.4-2.2	15-24	33-49	15-10	1.14-1.22	225-240	0.44-0.65
E	0.75-1.4	15-8	49-75	15-23	0.75-1.14	150-225	0.65-1.0
F	$\leq$0.75	$\leq$8	var.	var.	$\leq$0.75	$\leq$150	var.

Source: Highway Capacity Manual (TRB, 2000)

Prior to the 2000 edition of the HCM, the LOS A space requirement was 130ft^2/ped (12m^2/ped). Sorton of Northwestern University suggested this LOS A space requirement was excessive (Special Report 209, TRB, 1994). Indeed, the *Interim Materials on Highway Capacity* (TRB, 1980) recommended an even lower space threshold (3.7m^2/ped or 40ft^2/ped) than Sorton's recommendation. For the 2000 edition of the HCM, the LOS A space requirement was reduced to 60ft^2/ped (5.6m^2/ped).

As a point of comparison, Tables 2.3a and 2.3b compare LOS values in the HCM with those reported from other researchers. Tanaboriboon and Guyano (1989) developed LOS standards for Bangkok, Thailand. Their data in the table highlight the importance of cultural values and physical characteristics on LOS breakpoints. The authors note that one result of the difference between Thai and American LOS standards is that pedestrian facilities in Thailand can accommodate higher flows at a given LOS. Stating that capacity limitations do not normally dominate pedestrian facility concerns, Brilon (1994) stated that Germany's revised pedestrian LOS standards will have breakpoints based on density. The boundaries for Polus et al's 1983 study on pedestrian movement in Israel correspond to the three regimes of pedestrian flow reported by those researchers.

Table 2.3a: Comparison of Walkway LOS thresholds by Space (m^2/ped) and Flow Rates (ped/m/min)

United States of America				Germany	Israel	Thailand
	HCM	Fruin	Pushkarev-Zupan[a]	Brilon	Polus et al[b]	Tanaboriboon-Guyano
LOS	(m^2/ped)	(m^2/ped)	(m^2/ped)	(m^2/ped)	(m^2/ped)	(m^2/ped)
	-	-	>49[a]		-	-
A	>5.6	>3.2	12-49	>10	-	>2.38
B	3.7-5.6	2.3-3.2	12-4	3.3-10	-	1.60-2.38
C	2.2-3.7	1.4-2.3	4-2	2-3.3	>1.67[b]	0.98-1.60
D	1.4-2.2	0.9-1.4	1.5-2	1.4-2	1.33-1.66	0.65-0.98
	-	-	-	-	0.8-1.33	-
E	0.6-1.4	0.5-0.9	1-1.5	0.6-1.4	0.5-0.8	0.37-0.65
F	<0.6	<0.5	0.2-1	<0.6	unknown	<0.37
	-	-	-	-	-	-

[a]Instead of HCM LOS designations "A"-"B"-"C"-"D"-"E"-"F", Pushkarev and Zupan use "Open" - "Unimpeded" - "Impeded" - "Constrained" - "Crowded" - "Congested" - "Jammed"

[b]Instead of HCM LOS designations "A"-"B"-"C"-"D"-"E"-"F", Polus et al use A-B-C_1-C_2-D

Sources: TRB, 2000; Fruin, 1971; Pushkarev and Zupan, 1975b; Brilon, 1994; Polus et al, 1983; Tanaboriboon and Guyano, 1989

Table 2.3b: Comparison of Walkway LOS by Flow Rates (ped/m/min)

United States of America				Germany	Israel	Thailand
	HCM	Fruin	Pushkarev-Zupan[a]	Brilon	Polus et al[b]	Tanaboriboon-Guyano
LOS	(ped/min/m)	(ped/min/m)	(ped/min/m)	-	(ped/min/m)	(ped/min/m)
	-	-	<1.6[a]	-	-	-
A	<6.6	<23	1.6-7.0	-	-	<28
B	6.6-23	23-33	20-7	-	-	28-40
C	23-33	33-49	20-33	-	<40[b]	40-61
D	33-49	49-66	33-46	-	40-50	61-81
	-	-	-	-	50-75	-
E	49-82	66-82	46-59	-	75-95	81-101
F	var.	var.	0-82	-	unknown	101 or var.

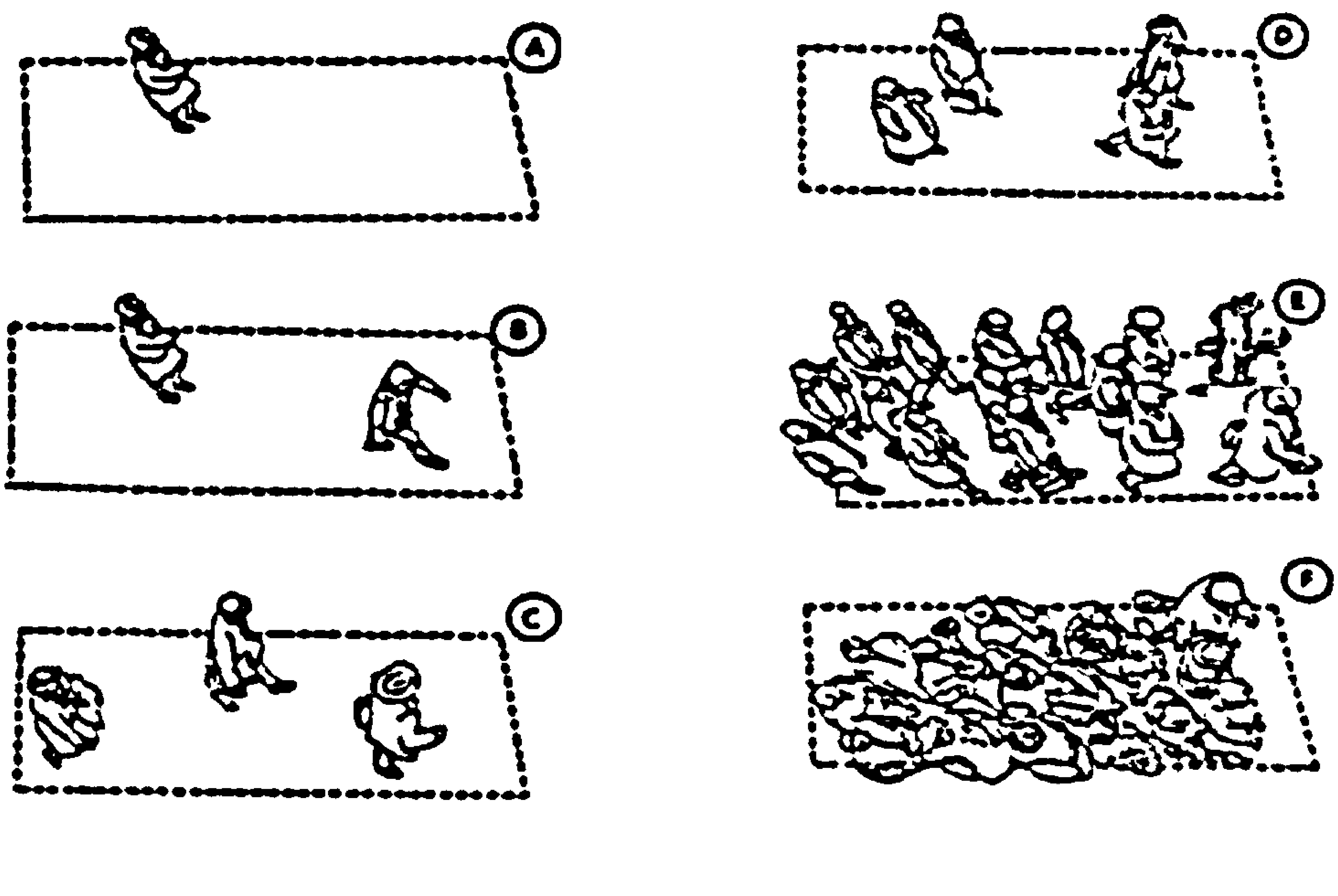
[a]Instead of HCM LOS designations "A"-"B"-"C"-"D"-"E"-"F", Pushkarev and Zupan use "Open" - "Unimpeded" - "Impeded" - "Constrained" - "Crowded" - "Congested" - "Jammed"

[b]Instead of HCM LOS designations "A"-"B"-"C"-"D"-"E"-"F", Polus et al use A-B-C_1-C_2-D

Sources: TRB, 2000; Fruin, 1971; Pushkarev and Zupan, 1975b; Brilon, 1994; Polus et al, 1983; Tanaboriboon and Guyano, 1989

The HCM then sets out the six LOS ranges in a diagrammatical form, to guide the analyst as shown in Figure 2.3 below.

Figure 2.3: Illustration of HCM Walkway LOS Thresholds



Source: Highway Capacity Manual (TRB, 2000)

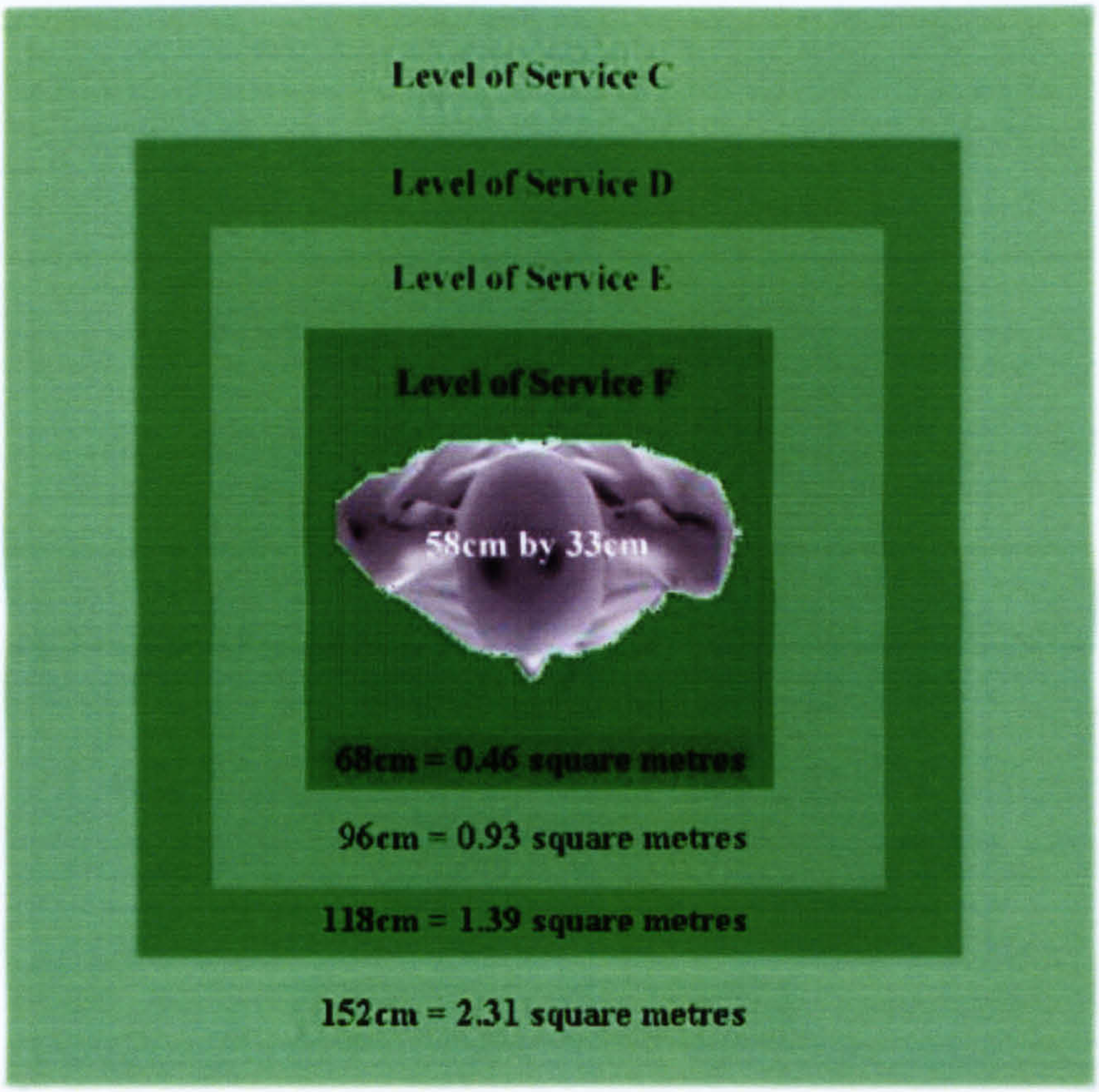
Fruin goes to great lengths to describe the applicability of his data and the LOS indicator, but many users take the LOS as a de facto standard without consideration of the local environments (Still, 2000). Body sizes differ and this needs to be considered for high-density environments (Still, 2000).

The 95 percentile means that in any given population 95 percent of that population will have dimensions less than or equal to the figures given above. These apply to the unclothed individual. Fruin made the assumption of adding 1½ inches (3.81 cm) to the breath and width, to allow for heavy clothing. Still (2000) believes this is an overgenerous allowance.

Fruin claims this represents restricted movement for most pedestrians. Observations at Wembley Stadium of crowds of much higher density contradicts these observations (Still, 2000). The reasons for this apparent contradiction are found in the relationships between the people and the local geometry, and the relationship of the speed distribution of the individuals in the crowd to the crowd flow volume (Still 2000). People do not all move at the same speed and hence complex conflicts arise. To allow for this, a recent study at the University of Warwick (Still, 2000) produced an alternative set of LOS ranges.

These were included in the pedestrian modelling computer software LEGION (Still, 2000). The model is described later in this Chapter, but Figure 2.4 shows the LOS areas.

Figure 2.4: Still's LOS Areas



Source: Still (2000)

Still's alternative set of LOS thresholds seem to be less generous than those of Fruin and certainly those recommended in the HCM.

Still, however, emphasises he is not stating that the Fruin or HCM LOS thresholds are incorrect. Clearly there is a margin for increased density and flow in a safe and non-threatening environment. The LOS standards, as a design criteria, are clearly an ideal guideline to achieve. But flow does not cease at the Fruin or HCM LOS range F, therefore appropriate measures for risk assessment at high density are needed.

Still states that *"crowds do not flow like fluids. They do not fill space in an even and regular manner"*. He termed this effect the *space utilisation function*. The measure of space utilisation is a central theme in the analysis of pedestrian movements and facilities, yet in confined spaces the local geometry was observed to effect and even dominate the crowd flow and behaviour (Still, 2000).

Stairs and Stairways

To allow for the determination of LOS thresholds for pedestrian networks (sometimes referred to as "arterials"), Virkler (1996) utilised a 20-year-old proposed ITE stairways standard (ITE, 1976), which provided space and flow values at various stairway LOS ranges. Virkler states that he modified this standard somewhat *"to ensure that the basic equation of traffic flow is satisfied"*.

Table 2.4 shows his recommended pedestrian LOS criteria. The values reflect ITE's flow values, Fruin's (1971) original breakpoints for stairway level of service, and Virkler's values for pedestrian speed and volume-capacity ratio. The LOS E values of 49 and 56 ped/min/metre described by Virkler and Fruin, respectively, are noticeably less than the 62 to 73 ped/min/metre capacity ranges found by Morrall et al (1995) in the Hong Kong and London transit systems.

Table 2.4: Pedestrian LOS Criteria for Stairs

LOS	Space (m^2/ped)	Flow Rate (ped/min/m)	Avg. Horiz. Speed (m/min)	(m/s)	v/c ratio
A	1.9	16	32	0.53	0.33
B	1.6-1.9	16-20	32	0.53	0.33-0.41
C	1.1-1.6	20-26	29-32	0.48	0.41-0.53
D	0.7-1.1	26-36	25-29	0.42	0.53-0.73
E	0.5-0.7	36-49	24-25	0.40	0.73-1.00
F	< 0.5	var.	< 24	< 0.40	var.

Source: Virkler, 1996

Crossflows

A crossflow is a pedestrian flow that is roughly perpendicular to and crosses another pedestrian stream. In general, one refers to the smaller of the two flows as the crossflow. Khisty (1982) notes that pedestrian crossflows can occur in almost any situation and are *"ubiquitous"*. Displayed in Table 2.5 are his suggestions for acceptable criteria regarding corridor crossflows. These values correspond roughly with the bottom half of HCM walkway LOS E; by terming them minimums and maximums, he seems to imply that his values establish LOS boundaries for crossflows.

Table 2.5: Capacity Thresholds for Crossflows

LOS	Speed (m/s)	Flow[b] (ped/min/m)	Density (ped/m^2)	Space (m^2/ped)
E[a]	1	75	0.8	1.25

[a]Khisty terms these threshold values *"minimums"* and *"maximums"*; by implication, this is LOS E

[b] *Total of the major and minor flow*

Source: Khristy, 1982

2.2.2.4 Pedestrian Networks

Virkler (1996) notes that the HCM's arterial analysis chapter (11) uses overall average travel speed as the measure of effectiveness in determining LOS. He recommends use of average travel speed for pedestrian arterials (routes) as well. Compared in Table 2.6 are his recommended travel speed values with appropriate speed values from the HCM's vehicular arterial analysis chapter.

Table 2.6: Comparison of HCM Vehicle Arterial LOS Criteria with Pedestrian Arterial Threshold proposals by both Virkler and North Carolina State University (NCSU)

Class I Vehicle Arterials				*Class III Vehicle Arterials*			*Pedestrian arterial threshold proposals*				
							Virkler		NCSU		ratio[d]
LOS	(m/s)	(mph)	(%FFS[a])	(m/s)	(mph)	(%FFS[b])	(m/min)	(m/s)	(mph)	(%FFS[c])	
A	16	35	88	11	25	93	80	1.33	3	95	90
B	13	28	70	8.5	19	70	70	1.17	2.6	84	70-90
C	9.8	22	55	5.8	13	48	60	1	2.2	71	50-70
D	7.6	17	42	4	9	33	50	0.83	1.9	59	40-50
E	5.8	13	33	3.1	7	26	35	0.58	1.3	41	30-40
F	< 5.8	< 13	< 33	< 3.1	< 7	< 26	< 35	< 0.58	< 1.3	< 41	30

[a] Percent of 18m/s (40mph) free-flow speed for Class I vehicle arterials that favour mobility

[b] Percent of 12m/s (27mph) free-flow speed for Class III vehicle arterials that favour access

[c] Percent of 1.4m/s (3.1mph or 84m/min) free-flow speed for pedestrian walkways

[d] Ratio of calculated minimum travel time to actual travel time, multiplied by 100 for easier comparison with "percent of free-flow speed" used for vehicle arterial thresholds

Sources: TRB, 2000; Virkler, 1996

Virkler's values represent an adaptation of pedestrian walkway and signalised intersection vehicular delay LOS standards. For a given LOS, the pedestrian arterial values represent an average travel speed, assuming the average walkway speed at that LOS with a delay over a 100m length equal to that experienced at a signalised intersection LOS. Examination of the above criteria reveals that one would have to maintain normal walking speeds throughout the entire arterial (e.g. essentially no stopping at signals or other nodes) in order to achieve the upper levels of service.

2.2.2.5 The Effects of Platoons of Pedestrians

Walkway Platoons

The companion volume, *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual* noted the effect of platoons on walkway flow. Table 2.7 summarises the initial research on platoons.

Table 2.7: Platoon-adjusted Walkway LOS Thresholds

LOS	Space				Flow Rate			
	Pushkarev-Zupan		Interim Materials		Pushkarev-Zupan		Interim Materials	
	(m^2/ped)	(ft^2/ped)	(m^2/ped)	(ft^2/ped)	(ped/min/m)	(ped/min/ft)	(ped/min/m)	(ped/min/ft)
A[a]	≥49[b]	≥530	12[c]	130	≥1.6b	≥0.5	6[c]	2
B	4-6	40-60	4-12	40-130	15-20	4.5-6	6-20	2-6
C	2-4	24-40	2-4	24-40	20-33	6-10	20-33	6-10
D	1.5-2	16-24	1.5-2	16-24	33-46	10-14	33-46	10-14
E	1-1.5	11-16	1-1.5	11-16	46-59	14-18	46-59	14-18
F	1	11	0.6-1	6-11	59	18	59-82	18-25

[a]Instead of HCM LOS designations "A" - "B" - "C" - "D" - "E" - "F", Pushkarev and Zupan use "Open" - "Impeded" - "Constrained" - "Crowded" - "Congested" - "Jammed"

[b]Values given by Pushkarev and Zupan for flow rates and space are within platoons

[c]Values given in the *Interim Materials* for flow rates and space are under average flow conditions

The LOS shown at each flow rate or pedestrian space level represents the walkway LOS (based on *Interim Materials* service levels) under these average flow rates when platoons arise

Source: Pushkarev and Zupan, 1975b; TRB, 1980.

Pushkarev and Zupan (1975b) note that earlier research found the ability to pass slow-moving pedestrians to be relatively unrestricted at space areas above 3.3m^2/ped, difficult between 1.7 and 3.3m^2/ped and essentially impossible below 1.7m^2/ped. Pushkarev and Zupan also compared average flow rates with possible flow in platoons. They found no difference between the flow conditions at any service level, except at that point in "Impeded" flow (approximately LOS B) when platoons begin.

The Interim Materials on Highway Capacity (TRB, 1980) contained platoon flow criteria. This work, simply rewrote the recommended walkway values up one level for platoons. The current HCM uses different walkway values for average flow rate and space at most service levels than those in the *Interim Materials*. Therefore, one cannot simply apply the values listed in the *Interim Materials* to the current HCM.

However, Bowman and Vecellio (1994) developed platoon flow LOS criteria based on a synthesis of the relationship between average and platoon flow described in the companion *Literature Review*, the 1994 HCM walkway standards for midrange LOS values (TRB, 1994), and the earlier work of Pushkarev and Zupan (1975b) for extreme values. For LOS A, they used Pushkarev and Zupan's relationship between average and platoon flow and defined this breakpoint to be just before the discontinuity, at 1.6ped/min/metre (0.5ped/min/ft), identical to the "Open" flow of Pushkarev and Zupan. For LOS B through D, they applied a metricised "rule of thumb" to the 1994 HCM walkway values, by subtracting 13ped/min/metre from walkway flow rates. For LOS E, and thus LOS F, they used the highest platoon flow rate found by Pushkarev and Zupan, 59ped/min/metre. The resulting values, shown in Table 2.8, provide a basis for determining the level of service experienced by people who travel in platoons.

Table 2.8: Suggested Platoon-adjusted Walkway LOS Criteria

LOS	Space		Flow Rate[a]	
	(m^2/ped)	(ft^2/ped)	(ped/min/metre)	(ped/min/ft)
A	49	530	1.6	0.5
B	8-49	90-530	1.6-10	0.5-3
C	4-8	40-90	10-20	3-6
D	2-4	23-40	20-36	6-11
E	1-2	11-23	36-59	11-18
F	1	11	59	18

[a]Flow rate in the table represent average flow rates over a 5 to 6 min period. The LOS shown is the walkway LOS under these average flow rates when platoons arise

Source: Bowman and Vecellio, 1994

Platoons at Transport Interchanges

Transport interchanges provide a special case of platoon flow. Davis and Braaksma (1987) analysed the pedestrian flow within an airport corridor by a "floating pedestrian" method, in which the surveyor measures parameters from within the pedestrian stream. Table 2.9 shows the LOS standards developed by the authors for platoon flow in transport terminals.

Table 2.9: LOS Thresholds for Platoon Flow in Transport Terminals[a]

LOS	Space	Flow Rate	Speed
	(m^2/ped)	(ped/min/metre)	(m/s)
A+	$\geq$2.3	$\leq$37	$\geq$1.4
A	1.7-2.3	37-46	1.3-1.4
B	1.3-1.7	46-57	1.2-1.3
C	1.0-1.3	57-68	1.1-1.2
D	0.8-1.0	68-75	1.0-1.1
E	0.7-0.8	75-85	0.7-1.0
F	$\leq$0.7	$\geq$85	$\leq$0.7

[a]Airports or other facilities where platoon flow is prevalent along pedestrian walkways

Source: Davis and Braaksma, 1987

By implication, the use of the term "transport terminal" refers to both an airport and to those other locations with tendencies for the platooning behaviour common in airport walkways (Young, 1999). Note that, although maximum speed and space occur at the highest LOS (A+ in the table), the maximum flow occurs at the boundary between LOS D and E. Also of note, the extremely high flows in these facilities warrant much less restrictive service criteria. To facilitate incorporation into the 2000 edition of the HCM, Davis and Braaksma's LOS A and B were consolidated into LOS B and LOS A+ was re-designated as LOS A. In effect, this expands the transport terminal LOS B to a range roughly coincident with platoon-adjusted walkway criteria LOS E. In addition, LOS E reflects the capacity thresholds suggested earlier. The recommended values in HCM are shown in Table 2.10.

Table 2.10: HCM Pedestrian LOS for Platoon Flow in Transport Terminals[a]

LOS	Space (m^2/ped)	Flow Rate (ped/min/metre)	Speed (m/s)
A	≥2.3	≤37	≥1.4
B	1.3-2.3	37-57	1.2-1.4
C	1.0-1.3	57-68	1.1-1.2
D	0.8-1.0	68-75	1.0-1.1
E	0.7-0.8	75-85	0.7-1.0
F	≤0.7	≥85	≤0.7

[a]Airports or other facilities where platoon flow is prevalent along pedestrian walkways

Source: Highway Capacity Manual (TRB, 2000)

General Pedestrian Movement through Transport Interchanges

It is not only interchanges with airport-style walkways which have been studied. Platforms and concourses as used in bus and rail stations have also been examined (for example, Daamen and Hoogendoorn, 2002). Guidelines recommending safe and appropriate dimensions and facilities have been published by various organisations including Railtrack (1997), now known as Network Rail, and the Chartered Institute of Transport (2000). The recommendations for levels of services are less generous than Fruin (1971) due to the need for a more stringent passenger safety requirement stipulated by the Health and Safety Executive (DETR, 1999) and/or Her Majesty's Railway Inspectorate (HMRI, 2002).

2.3 Modelling Pedestrian Flows

2.3.1 Background

Historically, compared to the level of research that has been done for motorized transport, there has been relatively little study and analysis of the factors that affect the quality of the walking environment. Evaluating the performance of a roadway section for the walking mode is far more complex in comparison to that of the motor vehicle mode. Whereas operators of motor vehicles are largely insulated in their travel environment and hence are influenced by relatively few factors, the pedestrian is relatively unprotected and is subject to a host of environmental conditions.

Sarkar (1993) articulates for many that the pedestrian in the roadside environment is subjected to a multitude of factors significantly affecting his/her feeling of safety, comfort and convenience. Accordingly, she classified these factors under two general performance measures describing the roadside pedestrian environment:

1) walkway capacity; and
2) the influence of the walking environment on the pedestrian.

As shown in the previous sections of this Chapter, the first performance measure, *walkway capacity*, has been widely examined and developed over the years. However, Sarkar (1993) showed this performance measure is limited in its applicability: it only evaluates conditions for an existing (or a planned) walkway and then, only from the perspective of "walking space" or effective walkway width available to the pedestrian.

In 1996, Sarkar then revisited her work and was disappointed to note to find that nobody had established an approach for the second measure. Several researchers and a number of planners have proposed qualitative measures of the *total quality* of the walking experience. Their approaches include numerous qualitative assessments relating to the pedestrian's *enjoyment* of the walking experience (e.g. convenience of the walking experience and the perception of personal security). Works by Khisty (1994) and Dixon (1996) are examples of methods that include a mixed combination of some factors of both performance measures.

However, both studies concentrated on safety factors and were very focused on this aspect. While this is important, to provide a complete picture of the walking environment and to design an "inviting" footpath, Sarkar believes other factors should be considered (Sarkar, 1996).

The following sections seek to pursue this train-of-thought, by discussing some of the most popular pedestrian models and techniques currently employed with a brief overview of their workings, looking at the concepts and techniques they use (which has been found to be common to all of them), and examining what data they typically require to assess pedestrian walking.

2.3.2 Review of Pedestrian Modelling Software and Techniques

2.3.2.1 Background

Pedestrian modelling software and techniques fall into two main categories; behavioural and movement models. The behavioural models are essentially two types: conceptual models and computer models.

Conceptual models include the observed, empirical and reported actions of individuals from questionnaire studies (e.g. Canter, 1985; Sime 1992). Computer models incorporate the simulation and behaviour of individuals with respect to their information seeking and processing. Behavioural models do not include the dynamics of crowds in their analysis.

Of the movement models there are two main types: these are the fluid or particle systems and the matrix-based systems. In the fluid category the applications of the Boltzmann Gas equations are used. Examples of computer software using this technique include EXODUS and RAMPAGE. In the matrix systems the use of the Fruin/HCM data is implicit. Examples of computer software using this technique include EGRESS, PFES and PEDROUTE. These, and other models, are described below.

2.3.2.2 The EXODUS Model

Galea (1997a and 1997b), at the University of Greenwich, adopted fluid dynamical models and coupled these with discrete virtual reality simulations of human movements. The resulting software, EXODUS, has been used in a number of major projects, worldwide. In his description of EXODUS he states:

> *"EXODUS was designed to simulate the evacuation of large numbers of individuals from large multi-floor buildings. The model tracks the trajectory of each individual as they make their way out of the building or are overcome by fire hazards such as heat and toxic gases. The model is a collection of 20 attributes that fall into four categories: Physical (age, weight, gender, agility), Psychological (patience, drive) positional (distance travelled) and hazard effects." (Galea, 1997a)*

On the basis of each individual attribute the model activates each and every simulated human and proceeds to assess the impact on the egress statistics. These attributes add to the computational intractability of testing, for example, what is the egress rate for the overweight?

2.3.2.3 The RAMPAGE Model

Cohen (1997) developed sophisticated particle simulation systems to model the human behaviour into reflex (immediate) reactions and inference (decision) reactions based on knowledge obtained from the scene. The principles behind his modelling are based on the Boltzmann gas equations which are discussed later.

His company, Animation Science, has applied the model to a number of well-known situations with iterative adjustment of behaviour until empirical results are reproduced. The main source of their calibration has been the work of Fruin (1971). Calibrations to these standards have already been shown in previous sections of this Chapter to be questionable.

There is limited historical data available for the development of simulation models. It is not feasible to test a large-scale crowd to destruction in order to gather new data.

Still (2000) has argued that the use of the Fruin data may leave sufficient margin for error and, provided the limits are understood, then these systems can be used in the design and operation of places of public assembly. The RAMPAGE product uses historical data and not the designers' own field studies.

2.3.2.4 Social Force Models

Helbing (1992, 1995 and 1997) has completed several years of research in the application of the Boltzmann-like gas-kinetic approaches. He describes a variety of human behaviours which are outlined below:

- pedestrians prefer to walk with an individual speed, which corresponds to the most comfortable walking speed as long as it is not necessary to move faster in order to reach the destination in time. The desired speeds within a crowd are a Gaussian distribution with a mean value of 1.34 metres per second and a standard deviation of 0.26 metres per second;

- pedestrians keep a certain distance to other pedestrians and borders (of streets, walls and obstacles). This distance is smaller the more a pedestrian hurries, and it decreases with growing pedestrian density. Resting individuals (e.g. waiting on a railway platform for a train, sitting in a dining hall, or lying on a beach) are uniformly distributed over the available area if there are no acquaintances among the individuals. Pedestrian's density increases (e.g. interpersonal distances lessen) around particularly attractive places. It decreases with a growing velocity variance (e.g. on a dance floor). Individuals knowing each other may form groups which are entities that behave similarly to single pedestrians. Group sizes are Poisson distributed; and

- pedestrians normally do not reflect their behavioural strategy in every situation anew but act more or less automatically (as an experienced car driver does). This becomes obvious when pedestrians cause delays or obstructions, e.g. by already entering an elevator or underground even though others still try to get off.

2.3.2.5 Passenger Flow Evaluation System (PFES)

Ando et al (1992) have developed a system in conjunction with the Japanese Research Institute, which is based on the principle that predefined crowd movements can be ascertained and a simulation obtained based on these factors. Grids are laid on the floor plan (maximum number 150 x 60) and each grid indicates a general direction, flow rate and predetermined speed/density relationship. It is effective but, as with all systems in this category, dependant on operator skills in creating the correct grid parameters.

The system is basically an application of the Fruin models with suitable adjustments for the Japanese profiles and speeds measured on their transit system (1.4 metres per second for free flow and an associated graph to determine the speed in various cross flows).

2.3.2.6 The EGRESS Model

Like the PFES model the system from SRD AEA Technology (Ketchell and Cole, 1993) is based on grids (in this case the grids are hexagonal). They use artificial intelligence techniques to determine how an agent will react in a variety of circumstances. They have based their artificial intelligence rules on the research of Canter (1985), Sime (1992), and Fruin (1971).

Canter and Sime are crowd psychologists. Their approach is fundamentally a cellular automation process in which the transition of people from cell to cell is based on an occupancy of the cells. They calibrate their data against speeds where experimental data exists. SRD AEA Technology demonstrated that the historical data is flawed in that it relies on homogeneous flow assumptions.

2.3.2.7 The PEDROUTE and PAXPORT Models

PEDROUTE is a computer simulation system which was originally developed for use in assessing pedestrian movements in London Underground stations (Annesley et al, 1989). The intellectual property rights were then sold to Halcrow Fox (now known as the Halcrow Group), who have continued to develop the model and have also produced a variant called PAXPORT for specific use at Transport Interchanges. PEDROUTE/PAXPORT have been used extensively to model pedestrian and crowd parameters around the world (Halcrow, 2002a and Halcrow, 2002b). They use an extension of the HCM/Fruin LOS concept and rely on that data being an accurate representation of the pedestrian crowd with respect to local geometry.

The emphasis is on the spatial shapes (layout) of the walking area and the amount of space available for the pedestrians to move. Since the layout of a walking area influences the behaviour of pedestrian flows, the model uses mathematical relationships between density in the walking areas and pedestrian speeds to model pedestrian walking behaviour.

Using the model, Clifford (1999) indicated that the speeds they measured were double that of the Fruin indicators. The system's performance was questioned, as the reliance on the HCM/Fruin data had been shown to be incorrect during their own research.

PEDROUTE/PAXPORT also suffer from inaccuracies when cross flows, concourses and other local effects do not have HCM/Fruin data (Still, 2000). In those cases the closest approximations are made.

2.3.2.8 The LEGION Model

LEGION is the name used to describe a collection of programs developed to analyse the dynamics of crowds. The heart of this suite is an algorithm which models the dynamics of the crowd by using a least effort algorithm. Details of the least effort algorithm is subject to a commercial non-disclosure agreement. However, Still (2000) describes the model as being able to treat every person (entity) in the crowd as an individual, calculating their positions by scanning their local environment and choosing an appropriate, humanlike, action.

The LEGION tools consist of a prototype development suite, a C library, a model builder and simulator (commercial products developed for client projects) and a re-player, which allows the user to view, review and analyse their models.

With LEGION it is possible to alter various parameters and study the effects of, for example, increasing the crowd density. The use of a simulation provides the user with two important perspectives. Firstly, the simulation provides insights to the nature of crowd dynamics; often it is the insight to the problem that leads to the solution. Secondly, the simulation can be used to prove or disprove a variety of relationships observed in the crowd, for example whether doubling the width of an egress route will double the flow of people.

2.3.2.9 The NOMAD Model

NOMAD (Hoogendoorn, 2003) is an *activity-based* model, where actions of the pedestrians are largely determined by the different activities pedestrians have planned to perform while being in the walking facility.

Given an activity pattern (ordered set of activities; e.g. buying a train ticket and subsequently getting to the train platform), and given the (multiple) areas where these activities can be performed (ticket counters, train platforms, etc), NOMAD determines the most likely areas where activities are performed and the most likely routes between them.

NOMAD allows for completely free route choice: pedestrians do not walk along linear, predetermined paths; rather, the routes are continuous paths in the continuous space. This set up, therefore, allows the model to distinguish different levels of pedestrian behaviour, namely:

- activity area and route choice level (tactical level); and
- walking behaviour (operational level).

The route choice and the activity area choice depend on the prevailing (pedestrian) traffic conditions, so when routes become congested, pedestrians avoid those routes provided that there are good alternative routes available. Within the model configuration, it is possible to define preferred walking areas (e.g. next to shopping windows, well-illuminated areas, etc.), as well as to include specific kinds of walking infrastructure, such as escalators and stairs.

While walking, pedestrians aim to adhere to the shortest route. However, due to encounters with other pedestrians, they might not always be able to do so. This holds equally for the interaction with obstacles and walls. If a pedestrian drifts away from the shortest route, the shortest route *from that point onwards* is used.

The modelling of the *operational walking task* (e.g. acceleration and interaction processes) is based on known empirical facts and theory on pedestrian behaviour. NOMAD automatically computes the effect of these factors on the pedestrian walking speeds, based on results of empirical studies, such as those reported by Weidmann (1993).

2.3.2.10 The SIMPED Model

SIMPED (Daamen, 2002) is primarily aimed at analysing the impacts of station designs and layout. The model can be applied to quantify the LOS of pedestrians while they are moving through the station and while they are waiting at a platform or in the hall. These situations can be simulated for existing stations, extensions of existing stations, stations under development and stations under design.

The emphasis is on the spatial shapes (layout) of the station and the amount of space available for the passengers to move. By dividing the flows of passengers by the areas of the available spatial shapes (layout), the average density is obtained and then comparisons with the HCM/Fruin LOS indicators can be made. This is exactly the same as the technique used in other models, including PEDROUTE (see Section 2.3.2.7 above).

Since the layout of a station building influences the behaviour of passenger flows, the SIMPED uses macroscopic relationships between density in the walking areas and pedestrian speeds to model pedestrian walking behaviour. Route choice and the performance of activities is based on individual pedestrians. Over-saturated bottlenecks, for instance before an escalator or near an entrance or exit, can already be identified and remedial measures sought and tested.

2.3.2.11 The PEDFLOW Model

The PEDFLOW (PEDestrian FLOW) project is concerned with the development of a microscopic model of pedestrian movement in a congested urban environment (Willis et al, 2001). The model simulates the behaviour of individuals as they negotiate a virtual walking environment. Pedestrians are modelled as autonomous agents travelling to a predetermined goal and reacting to obstructions (e.g. bus stops, other agents) according to a set of behavioural rules.

In order to ensure the rule set represents local behaviour, the rules need to be developed according to empirical data: a combination of observational and interview techniques are used to identify and quantify different movement behaviours (e.g. overtaking, yielding) in response to particular obstructions (e.g. bus stop, approaching person) given a particular set of environmental and personal circumstances.

The model utilises a single rule set that is made specific to each agent by the incorporation of parameters specific to that pedestrian. It is used to evaluate infrastructure changes intended to promote walking in the urban environment. Verification of the model is achieved by a series of before and after experiments in which the area to be modelled is video taped before and after an infrastructure change (Willis et al, 2000).

Automated analysis of the video tapes enables the extraction of behavioural patterns to determine any changes in behaviour. This is then further analysed to determine whether the rule set needs modification to capture any behavioural changes.

2.3.2.12 Specific Uses of the Models

EXODUS and LEGION are commonly used to simulate the evacuation of people from large multi-floor buildings.

RAMPAGE models the reflex reactions of pedestrians based on the characteristics of the local scene.

Social Force Models are useful for examining the characteristics of specific groups of pedestrians (e.g. the statistical distributions of their walking speeds, travel times, etc).

PFES, EGRESS and PEDFLOW define the walking area in grids and are mainly confined to micro-level analysis of crowd movements.

PEDROUTE and PAXPORT, however, can be used for area-wide studies and are not confined to the micro-level. PAXPORT is a variation of PEDROUTE specifically for use in analysing passenger stations and interchanges. SIMPED is also primarily aimed at analysing the impacts of station designs and layouts.

NOMAD tries to model pedestrian movements based on the range of activities available to them in the local area. This is useful in the study and design of land-use changes, estimating the numbers of pedestrians generated to/from an area and the affects this might have on the operational conditions of the network.

2.3.3 Commonalities in Pedestrian Modelling

2.3.3.1 Fundamental Speed-Flow-Density Relationships

The common element in these pedestrian models is the need for a reasonably accurate description of the walking environment pedestrians are exposed to, the factors which make up the characteristics of the walking environment and details of the pedestrians likely to use the facility. All these models use a series of relationships to describe the way a pedestrian (or group of pedestrians) would behave given a specific set of events and/or conditions.

The concepts and techniques they use involve some sort of description of walking speed, pedestrian flow and/or crowd density, and how they relate to each other and interact with themselves or the surrounding area. These are commonly known as speed-flow-density relationships, and can be disaggregated by different categories to represent, for example, different walking environments, pedestrian groups, times of day, etc.

All the models use some form of description of the physical layout of the walking area and the amount of space available for walking. Dividing the observed or estimated flows by the available area yields the average density and hence comparisons with the HCM/Fruin LOS indicators can be made. This assumes the layout of a walking environment influences the behaviour of pedestrian flows. Relationships between pedestrian speeds, flows and densities are used to model pedestrian walking behaviour.

Chapter 13 of the 2000 edition of the HCM begins with a description of the basic principles of pedestrian traffic flow on sidewalks, crosswalks and street corners. It provides the following relationship among fundamental pedestrian flow parameters (from Fruin, 1971):

$$V = S / M$$

where: V = flow or volume;

S = speed; and

M = pedestrian area module ("space") = 1/density.

The chapter makes use of two distinct descriptive measures of pedestrian facility performance. The units ped/min/m (or ped/min/ft) width represents a pedestrian *flow rate* (ped/min), normalised by width (m or ft). The units of m^2/ped (or ft^2/ped) represent the average *space available* (in m^2 or ft^2) per pedestrian (ped). Chapter 13 also provides several speed-space-flow graphs from Pushkarev and Zupan (1975a); these graphs summarise various field studies from both Europe and the United States, as reported by transportation researchers Hankin and Wright (1958), Oeding (1963), Older (1964 and 1968), Hoel (1968), and Navin and Wheeler (1969) and Fruin (1971). Noted in this chapter is that speeds decline as flow or density increases.

The HCM, relying on the field research reported by Pushkarev and Zupan (1975a), notes that all movement effectively stops at 2 to 4 ft^2/ped (about 0.2 to 0.4m^2/ped). Pedestrians can choose their preferred walking speed with low pedestrian volume, but both flow and speeds decline under crowded conditions.

Pushkarev and Zupan (1975b) noted in earlier research that pedestrians prefer a body buffer zone space of 0.27 to 0.84 m^2 and that *"unnatural shuffling"* begins when space falls below 0.75 m^2/ped.

At a minimum, the data required to model the movements of pedestrians and assess them against the HCM/Fruin LOS indicators is as follows:

- average speed of the pedestrian(s) – this could be for different groupings, disaggregated by different walking environments;

- the (average) flow of pedestrians, relative to the average speeds identified above; and

- the (average) crowd density, again relative to the average speeds identified above but also relative to the identified flows.

2.3.3.2 Pedestrian Flow Performance

Having identified the pattern and characteristics of pedestrian movements through the study area, these can then be compared against the HCM/Fruin LOS indicators to check the performance of the walking environment/facility or any other tests. For example, in motor vehicle traffic modelling it is common practice to identify the performance of a traffic network to the quantity of motor vehicles using it at a specific point in time. This could be estimates of the lengths of vehicle queues or time spent in delays. Helbing (1992, 1995 and 1997) proposed a pedestrian flow performance to evaluate the performance of a walking environment using uncomfortability index and delay index.

Effectively, pedestrian flow performances are numbers that measure the efficiency of pedestrian flow. By comparing one set of performance indicators against another, one can identify areas needing attention, which design is better than others, what is the most cost-effective solution, etc. They measure direct or indirect indicators of the interaction between pedestrians and the interaction between pedestrians with the walking environment. An example of a direct indicator is the average walking speed and an example of an indirect indicator would be the overall result of this walking speed on the network (Khisty, 1994).

Individual and average delay uncomfortability indices (e.g. levels of services), and speed are typical examples of pedestrian flow performance. They measure the result of the interaction among pedestrians and interaction between pedestrians with the facilities. They measure pedestrian interaction indirectly. Pedestrian flow performance is a broader concept than merely flow variables. Since traditional flow variables, such as pedestrian headway, flow, speeds and area also measure the interaction between pedestrians indirectly, they are also part of the pedestrian flow performance (Dixon, 1996).

The pedestrian flow performance can be measured through distances, widths and direction of travel. It may be valued over time as a change of distances and direction (e.g. speed) or as a rate of change (e.g. acceleration). They may be quantified for an individual at a specific time or a group of pedestrians over a wide range with a series of surrounding factors. Variation of ratios, indices and comparisons against some references may also produce different kinds of pedestrian flow performance (Naderi, 2002).

2.4 Effects of Pedestrian Characteristics and Walkway Environments

2.4.1 Pedestrian Types

The debate surrounding the importance of pedestrian planning is, on the whole, less developed than that for passenger movements. This is very surprising, given that the National Travel Survey shows that up to 80% of trips are less than 1 mile in length (DTLR, 2001). However, it seems the sheer number of cars on the road has made the government and local authorities concentrate on the passenger modal choice issue, up until the 1998 Transport White Papers (DETR, 1998 and The Scottish Office, 1998).

A large number of studies and guidelines (e.g. May and Hopkinson, 1991; Cullen, 1997; and IHT, 1997) have examined the options for effecting a change in modal split, but overwhelmingly these studies have focused most of their attention on the passenger market. However, many (e.g. Wegmann et al, 1983; Wigan, 1995; and Bendixson, 1997) argued that the study of pedestrians should not be viewed as inferior to that of passenger traffic and this is increasingly being seen in studies of transport growth and the resulting problems (DOT, 1996; DETR, 1997; and Steer Davies Gleave, 2001). Those studies which were carried out are reviewed in this Section, with a view to identifying any gaps in the research and weaknesses in current practice.

2.4.1.1 Trip Purpose

A number of studies have looked at the effects of trip purpose, and subsequent effects on pedestrian walking habits. One of the earliest was Older (1968), who looked at the movement of pedestrians on footways in shopping streets.

He assumed most of these pedestrians would be shoppers and concluded the walking speeds calculated would be applicable to shopping facilities only. He also claimed that pedestrians walked much slower during shopping than during other trip purposes, primarily due to the fact that they tended to stroll instead of stride, stop to look in windows and travel with children or carry baggage.

O'Flaherty and Parkinson (1972) have also looked at pedestrian movements on a city centre footway. Their findings seemed to reinforce that of Older's, and when White (1994) undertook a similar exercise over 20 years later, his findings were remarkably similar.

Lautso and Murole (1974) studied pedestrian traffic in Helsinki, specifically looking at times of the day when people would be travelling to and from work. They found walking speeds were higher than those quoted by Fruin and concluded it was due to the fact that people were in a hurry to go to work or catch the shops before they close en route to their home. This seemed to have been confirmed by MacDorman (1977), who studied the characteristics of walking speeds in the central business district (CBD) of Washington, D. C.

May and Hopkinson (1991) looked at a wide range of walking areas and time periods. In particular, they looked at the different perceptions of the pedestrian environment using a combination of survey techniques including questionnaires. They found the type of trip was statistically significant at influencing the speed of walking, and seemed to confirm the findings of previous researchers.

As expected, walking speeds are different in other pedestrian environments, for example CBD's. Ratnayake et al (1991) showed variances in pedestrian speeds which were correlated with the time of the day, outside temperatures and trip purpose. It is not just European and American countries where differences in walking speeds have been detected for differing trip purposes. Al-Masaeid et al (1993) studied data from various CBD areas in developing countries, including the Middle East and North Africa. They identified significant variations, and proposed a new set of pedestrian speed-flow relationships to be used instead of those in the HCM for these countries.

In addition, Pickett (1979), when he examined pedestrians in tourist areas and popular visitor attractions in York, suggested that tourists tend to use direction signs more than other groups of pedestrians. This suggests that there is a reaction to the physical environment and trip purposes could all contribute to each pedestrian's selection of their unimpeded free-flow characteristics.

These studies seem to confirm that there is a great deal of potential variability in individual pedestrian walking speeds, flows and densities. However, what is noticeable in the above studies is the fact they only looked at walking speeds at limited LOS ranges. This can be viewed as a common weakness. Although they quoted different results for different LOS ranges, the highest (most dense) LOS's were usually obtained by extrapolating the results from the surveyed lower LOS ranges to cover the other areas where data was not available. This was due, in part, to a lack of suitable data and opportunities where denser LOS values could be observed.

These studies seem to have been carried out using limited surveys, predominantly manual data collection methods, which invariably led to 'snap shots' of movements. One could argue they are not necessarily typical of longer periods. Furthermore, since they contain small numbers of observations, over short intervals of time, it would be interesting to check their validity by surveying conditions in denser LOS ranges and comparing them.

2.4.1.2 Age and Gender

The literature review suggests men and women have different walking speeds, flows and density relationships. White (1994) showed pedestrians might vary their walking speeds over a wide range, when unimpeded by crowd density or other frictions. He plotted the distribution of free-flow walking speeds using data obtained from surveys of about 1000 non-baggage-carrying pedestrians. On the basis of these surveys, he concluded average free-flow walking speed for males, females and the combination of all pedestrians in the surveys was 81, 76 and 80 m/min, respectively. Average speeds were found to decline with age, but individual slow and fast walkers were observed in all age groups.

As far as age is concerned, a controlled study by Murray (1986) of walking speeds for men, ranging in age from 20 to 87, revealed that normal walking speed declined with age, but that by increasing pacing rates and stride lengths, all participants in the study were capable of exceeding their normal relaxed walking speeds by about 40%.

They concluded that this would indicate that a healthy person in their 40's in a hurry could exceed the normal relaxed walking speed of a 20-year-old. Normal walking speeds declined from 84 m/min for the 20-to-25 age group, to 65 m/min for the 81-to-87 group, with most of the speed decline occurring after the age of 65. Fast walking speeds declined, respectively, from 134 to 89 m/min, with a similar more pronounced decline after the age of 65. These findings were similar to those of Coffin and Morall (1995), and also Knoblauch et al (1995).

Age has been shown to affect walking speeds in various medical studies. Edlmann and Pitcairn (2000) used video analysis to look at the individual differences in road crossing ability and associated walking characteristics in young children and adults (mean age 7 years 2 months and 20 years 6 months respectively). Results showed there were large and significant differences between adults and children on total crossing speeds. In 2000, Maylor et al (2001) undertook a psychological study to look at the effects of walking activities, and whether they are affected by age and also if pedestrians are carrying out certain tasks while walking (e.g. following direction signs, talking on a mobile telephone, carrying baggage, etc). They observed the behaviour of 70 participants aged 20-79 years. Unsurprisingly, they found that memory recall declined with increasing age but they also found significant differences in speed. Walking stability and speeds declined with age; moreover, there was support for an earlier finding that speed-decline was greatest when performing other tasks. The results suggest that walking can be affected by age and also certain types of cognitive activities (depending on the age of participants, the type of cognitive task and the cognitive processing required).

2.4.1.3 Pedestrians who carry Bags and Luggage

Naturally, as would be expected, the literature search seems to suggest carrying baggage also effects pedestrian movements. Virkler and Elayadath (1994) showed that the effects of carrying bags or luggage can encourage pedestrians to walk slower than they would, even if the weight of their luggage is not of a sufficient size to seriously affect them. Furthermore, Bowman and Vecellio (1994), who looked at pedestrian walking speeds and conflicts at urban median locations, indicated that commuters carrying brief cases did have their walking speeds affected by their baggage. This raises an opportunity to carry out similar research to test this theory.

2.4.2 Pedestrian Environments

In the previous section an examination was presented of the general literature relating to the effects of different types of pedestrians on walking. Reviewed in this section is the literature on the role of various types of walking environments and their physical characteristics: gradients, widths of footpaths, etc. It discusses the main issues pertaining to walking environments and highlights the principal areas in which attention has been focused thus far in past studies.

2.4.2.1 Gradients

Nitzburg et al (1996) carried out field studies of pedestrian walking speed and start-up times and showed that there is no measurable effect on walking speeds due to grades up to 3%, but that there is a gradual linear decline in speed for steeper grades. This seems to confirm a previous study by MacDorman (1977) and found no statistically significant differences in walking speeds due to grades of up to 3%.

These findings were similar to the recommendations of Robertson et al (1994). Furthermore, in a controlled study by Wigan (1995), it was found that the average walking speeds decreased by up to 11.5% with positive gradients from 5 to 10%, and by 25% for a positive slope of up to 20%.

2.4.2.2 Walkway Widths

Surprisingly, very little research seems to have been carried out on the effects of variable widths of pedestrian walkways. When widths are considered, it is usually in confined areas such as underground stations and associated tunnel connections (Annesley et al, 1991) or railway platforms (Buckman and Leather, 1994). Clearly, the results from studies of these types of pedestrian environments are very site-specific and it could be argued they are not transferable to general pedestrian planning studies. Therefore, this suggests there is a need for further research.

2.4.2.3 Kerb Effects and Street Furniture

An interesting point suggested by Pushkarev and Zupan (1975a) was that pedestrians tend to keep 0.30 to 0.45 metre lateral clear distance between themselves and the kerb line. The HCM (TRB, 2000) also noted a spacing of 0.3 metres adjacent to building lines and along the edges of passageways.

Consequently, Harris (1991) suggested that this lateral distance should be deducted from the walkway dimension when determining effective walkway width, however there is no evidence in the literature reviewed during this research to support this hypothesis in the walking environments of the UK.

As far as street furniture is concerned, studies by Older (1968), Roddin (1981) and Botma (1995), of pedestrian behaviour have shown that pedestrian interactions (such as eye contact, speed and direction tracking, and evasive manoeuvring) occur at inter-person distances of up to between 5.5 to 7.9 metres, with average pedestrian area occupancies up to between 72 and 79 m^2/person.

The different sets of research seem to confirm each others findings, which show that increased pedestrian density, or decreasing area occupancy, results in a negative sloping curve of pedestrian walking speeds and pedestrians are able to adjust appropriately to the obstruction effects of street furniture. Since street furniture is usually placed so as not to completely obstruct pedestrian movement, only small variations are caused.

This seems to confirm Fruin's (1971) assumption that the most significant determinant of pedestrian walking speed is pedestrian density. According to his findings, normal walking requires sufficient area for unrestricted pacing, and for sensory recognition and reaction to potential obstacles. As pedestrian density increases, pedestrian speed is decreased, because of the reduction in available clear area for locomotion. As a result, all pedestrian speeds tend to have less variability as increased crowd density restricts the ability to bypass slower-moving pedestrians, and to select their desired walking speed. Fruin's walking speed curve indicates that mean speeds for dense pedestrian flows are approximately normal, up to a certain point after which pedestrians are forced into a restricted and uncomfortable shuffling motion and then into immobile queuing.

2.4.2.4 Two-way Pedestrian Friction Effects

The adaptability of the walker to minor pedestrian traffic friction has been noted in research by various studies including Navin and Wheeler (1969), Pushkarev and Zupan (1975a), Polus (1983) and Rouphail et al (1998). The studies suggest a minor traffic flow proportion of 10% of the total flow (e.g. 90:10 directional split) would have only a slight affect (e.g. approximate 15% reduction in potential walkway capacity). Unsurprisingly, as the minor pedestrian flow proportion increases, its detrimental effect increases, but its affect on capacity is actually reduced since the shear volume of flow becomes the dominant factor.

Adler and Blue (1999, 2000 and 2001) suggested that with a 50:50 pedestrian flow mix, the two-way traffic capacity of the walkway was about equal to its one-way capacity. This equalising effect is due to the fact that smaller volume reverse-traffic flows are dominated by the larger major flows, forcing the pedestrian moving up-stream to dodge and weave through the on-coming horde. This reduces the traffic efficiency of the section but, as the minor upstream flow gets larger, this one-way domination is reduced, and the walkway section receives more balanced usage. Unlike on-street locations, there is little evidence for the effects of two-way pedestrian friction on off-street walkways. What is available can be seen in ITE (1976) who concluded that off-street weaving had less impact on pedestrian speeds, flows and densities. What is clear from this is that very few ratios of two-way directional splits were examined.

2.4.2.5 Different Location Effects

The literature also suggests different locations have different effects on pedestrian movements. For example, Al-Masaeid et al (1993) developed pedestrian speed-flow relationships for CBD areas in developing countries, and compared them to the average values quoted in the 1985 edition of the HCM. Their results indicate that the values of bi-directional CBD walkways specified in the HCM are not applicable to modern walking characteristics even if a reduction factor is applied to consider the bi-directional effect. This was also confirmed by other studies into CBD's in Hong Kong (Morrall et al, 1995) and America (McLeod, 2000); shopping areas in the Netherlands (Hoogendoorn, 2003), Germany (Brilon, 1994) and the UK (Older, 1968; O'Flaherty and Parkinson, 1972; Leake et al 1991); residential areas in Helsinki (Lautso and Murole, 1974); and all-purpose areas in Bangkok (Tanaboriboon et al, 1989) and Tanaboriboon et al (1986). The needs of pedestrian facilities in suburban and developing rural areas was examined by Smith et al (1987), and in underground walkways by Zacharias (2000).

While all these studies were very useful, they seemed to concentrate on direct comparisons of walking data for CBD's or shopping areas or residential streets in different countries and compare them to average values in the HCM or the results of other studies on similar types of walking areas. It would be interesting to compare walking data for CBD's, shopping streets and other areas from the same town, city or country rather than one type of walking environment in one country versus another type of pedestrian area in another country. This could be helpful in providing a like-for-like (in geographical terms) comparison.

2.5 Discussion

This Chapter has introduced the processes used to analyse the movements of pedestrians, their concepts and key indicators. Brief details of some of the most popular pedestrian models employed were set out. A review of past studies and published literature on pedestrian planning has also been presented.

The majority of this literature review seems to suggest a lack of understanding of all the complexities of walking characteristics and the extent to which variations occur both within and between different walking conditions.

To enable walking to play a greater role in transport planning requires a better understanding of the opportunities and barriers facing pedestrians in the 'real world', otherwise there is a danger pedestrian facilities will not be planned properly and the laudable walking policies of the transport White Papers may not fulfil their full potential.

In particular, the findings of this Chapter suggest the following:

- there are contradictions and uncertainties in some of the current guidelines and approaches to pedestrian modelling;

- only certain levels of pedestrian densities/LOS ranges seem to have been examined, and the subsequent relationships developed have been based on actual data measured. Other, more dense, LOS ranges seem to have been developed by extrapolation of the relationships of the lower densities;

- pedestrians consist of many individuals with differing walking characteristics. In the main, pedestrian modelling tends to use a standard relationship of speeds, flows and density for all types of pedestrians, even though research suggests there is a need to be able to distinguish between the various different types of pedestrians. This would allow pedestrian flows to be proportioned into appropriate groups, and each group to be analysed using the most relevant speed, flow and density characteristics.

- pedestrians react to their environment, and are influenced by its geometry and other factors. While there seems to be some research into relationships for different types of pedestrian environments, this seems to have been carried out either using limited data or concentrating on one type of walking environment; and

- pedestrians cluster and move in groups, and self-organise at levels of high density.

The above suggests that the current practices do not fully understand or take cognisance of the above issues. Still (2000) speculates that complacency, over-dependency on the guidelines and lack of appropriate data may be reasons for these weaknesses. However, there can be no doubt that there are characteristics of pedestrian movements which do not form part of current practices and guidelines. It can therefore be concluded that there exists a need to produce a reliable system for a more holistic means of modelling pedestrian movements. It should have as few inputs as possible and be able to determine the relationship of the interactions between people, local geometry and environment.

The current HCM uses pedestrian space as the primary measure of effectiveness (MOE), with mean speed and flow rates as secondary measures (Table 2; TRB, 2000). In particular, the HCM's arterial analysis chapter (Chapter 11; TRB, 2000) uses overall average travel speed as the MOE. The review of industry practices in the UK and other parts of Europe by Zegeer et al (1994) has shown that speed is predominantly used as a MOE, and also as a means of testing the effectiveness of enhancements to existing walking facilities or comparing different designs of new infrastructure. Furthermore, some researchers like Virkler (1996) have modified the various speed indicators for use in their research while others like Al-Masaeid et al (1993) have adapted them for use in their countries. Nevertheless, in all these cases the main MOE is speed.

Given the findings of the literature review in this thesis showed there are a wide number of factors potentially influencing pedestrians this raises the question about the appropriateness of using speed on its own as a suitable MOE. This question has been investigated by Khisty (1994) who developed a framework to assist with the evaluation of pedestrian facilities, by attempting to provide a holistic means of examining pedestrian interactions with their surrounding environment and by looking beyond the LOS concept.

During the author's research or his experience of working in industry, he has not been able to find any published case studies or examples where speed has not been used either by itself or in combination with pedestrian space or flow as the main indicator for effectiveness.

3 OVERVIEW OF TRAVEL PATTERNS IN THE UK AND THE ROLE OF WALKING

3.1 Introduction

Described in Chapter Two was a review of past studies and published literature on pedestrian planning. However, this is only part of the picture, in that it does not explain why it is important to have robust means of studying walking movements and designing pedestrian facilities. This is discussed in this Chapter, which helps set the scene for this research and demonstrates how important walking is to a well-balanced and sustainable Government transport strategy.

3.2 Government Policies and the role of Walking

In 1997, the new Labour government decided to raise the profile of walking as a mode of travel and since then has provided renewed focus on providing quality pedestrian facilities in its national integrated transport strategy set out in the two transport White Papers (*Travel Choices for Scotland*, The Scottish Office, 1998 and *A New Deal for Transport: Better for Everyone*, DETR, 1998). The renewed initiative by the Government in its two Transport White Papers has resulted in a series of projects for new pedestrian facilities or improving existing infrastructure, and this has resulted in a renewed need for better pedestrian planning practices. There is clear evidence that local authorities are now providing more facilities to encourage much more walking, and reverse declining trends (for example Gaffron, 2002 and Spokes, 2003).

There appears to be an emphasis by the Government on increasing the demand for walking or at least stabilising its decline (DETR, 2000 and SDG, 2001), though there is more debate on the rate and time this will happen. There is little in the way of official forecasts, with those published in England only (10 Year Plan, DETR, 2000) predicting that the volume of trips, in terms of trip miles, would increase by between 5% and 15% from 2000 to 2010. These forecasts are based upon industry-standard transport modelling techniques and make no allowance for other developments that might modify or break this relationship.

3.3 Travel Patterns and Walking Trends

Using data from the National Travel Survey (DTLR, 2001), it is possible to see how travel patterns have developed and what role walking has in modern trip-making. This helps set the scene for this research, and shows how important walking is to a well-balanced and sustainable Government transport strategy.

3.3.1 About the National Travel Survey

3.3.1.1 Background

The National Travel Survey (NTS) covers the United Kingdom, excluding the most remote parts of Scotland. The 1998/2000 NTS consists of data from the latest three years of the continuous survey that began in July 1988. The size of the 1998/2000 database is similar to that for 1989/91, 1992/94 and 1995/97. It is also similar in size to the ad-hoc surveys carried out over twelve months in 1965, 1972/73, 1975/76, 1978/79 and 1985/86.

During the period January 1998 to December 2000, individuals in 9,390 households completed a seven-day travel diary, covering all travel over 50 yards in distance. Details collected included purpose, method of travel, time of day and length of journey. They also provided personal information, such as age, sex, working status, car access and driving licence holding.

The period covered by most observations in the NTS is three years, because the annual sample size of the continuous survey is about one-third that needed to provide reliable information about trips undertaken.

3.3.1.2 Uses of the NTS

The NTS is carried out in order to provide a better understanding of the use of transport facilities made by different sectors of the population, and trends in these patterns of demand. Extensive use was made of NTS data in the formulation of policies in the White Paper *'A New Deal for Transport'* (DETR, 1998), the Scottish equivalent *'Travel Choices for Scotland'* (Scottish Office, 1998) and in *'Transport 2010: The 10 year Plan'* (DETR, 2000). The 10 year plan includes targets and indicators which will be monitored by the NTS. Other important uses include the forecasting of future travel levels and considering how poor transport facilities exacerbate problems of social exclusion.

3.3.2 Travel Trends

3.3.2.1 Average Trips Rates, Lengths and Times

Since the early 1970s the average number of trips made by UK residents has fluctuated at around 1,000 a year, or about 20 per person per week (Table 2.1; DTLR, 2001). The average number of trips made in 1998/2000 was 8% higher than in 1972/1973. Over this period, the average trip length increased by 42%, from 4.7 miles to 6.6 miles. This led to an increase of 55% in the overall distance travelled, from about 4.5 to nearly 7 thousand miles per person a year.

In spite of this major increase in the distance travelled, the average time spent travelling in 1998/2000 (360 hours per person) was almost the same as in 1972/1973. This is a result of major changes in the methods of transport used, with trips on foot and by bus being replaced by longer but faster trips by car. Details of changes in trips by mode of travel are given in Section 3.3.3.

3.3.3 How People Travel

3.3.3.1 Distance Travelled

Shown in Table 3.1 are the changes in the distance travelled per person per year over the last 25 years, for different modes including walking. Trips may include more than one mode of transport, and the NTS records the mode used at each stage of a trip. The distances shown in this table have been aggregated from these individual stages, whereas later tables give details of the distance travelled according to the main mode of each trip. The main mode is the mode used for the greatest length of each trip.

Table 3.1: Average Distance Travelled by Mode of Travel (1975/1976 to 1998/2000)

	Miles per Person per Year						% Change
	1975/6	1985/6	1990/1	1992/3	1996/7	1999/0	1990/1 to 1999/0
Walk	255	244	237	199	195	185	-21%
Bicycle	51	44	41	38	39	38	-8%
Car	3,199	3,796	4,806	4,964	5,187	5,355	20%
Bus/Coach	483	406	398	355	345	346	-36%
Rail	327	336	415	348	345	428	19%
Other	425	491	578	535	555	491	-15%
All Modes	4,740	5,317	6,475	6,439	6,666	6,843	6%

Source: National Travel Surveys (DTLR, various years)

The table shows that there was a 6% increase in the distance travelled over all modes since 1989/1991, whereas walking fell by 21% during the same period. In comparison to the fall in walking distance, the distance travelled by car (both passengers and drivers) rose by 20% since 1989/1991.

The car is by far the dominant form of transport, accounting for almost four fifths of the total distance travelled in 1998/2000. As car travel increased, so travel on foot declined.

3.3.3.2 Number and Length of Trips

Displayed in Table 3.2 are the number of trips per person per year, by the main mode of the trip. The total number of trips made has remained reasonably constant over the years, although there has been a slight fall over the latest period. Car is the most frequent mode of travel, however walking is the second most frequent method of travel by main mode, far more than all other modes combined.

Table 3.2: Trips and Average Trip Length by Main Mode (1975/1976 to 1998/2000)

	Miles per Person per Year				Average Trip Length (Miles)			
	1990/1	1992/3	1996/7	1999/0	1990/1	1992/3	1996/7	1999/0
Walk	328	306	293	271	0.6	0.6	0.6	0.6
Bicycle	21	18	17	16	1.9	2.0	2.3	2.4
Car	619	618	637	639	8.3	8.5	8.6	8.7
Bus/Coach	75	70	64	60	71.1	67.4	67.2	69.3
Rail	18	17	17	19	40.8	39.9	38.6	42.0
Other	30	24	24	25	27.1	33.4	31.2	34.2
All Modes	1,091	1,053	1,052	1,030	5.9	6.1	6.3	0.1

Source: National Travel Surveys (DTLR, various years)

The number of walking trips each person made in a year fell by 17% although walking still makes up about a quarter of the total number of trips. Conversely, the number of trips each person made by car each year rose by 3% when compared with 1989/1991, with this increase being mostly from car driver trips (as opposed to car passengers).

3.3.3.3 Distribution of Trip Lengths

Table 3.3 shows the distribution of lengths of trips made by different modes of travel. By far the largest proportion is made up of walking trips under 1 mile in length. Comparisons with previous NTS data shows the number of trips under a mile has been steadily decreasing, and is down by almost a fifth on the number in 1989/1991 (DTLR, 2001). In total, 69% of trips were less than five miles and trips on foot accounted for four fifths of journeys under one mile.

Table 3.3: Trips per Person per Year by Distance and Main Mode (1998/2000)

	Under 1	1 to 2	2 to 5	5 to 10	Over 10
Walk	210	49	12	-	-
Bicycle	4	5	5	1	-
Car	44	112	209	131	99
Bus/Coach	2	10	30	12	5
Rail	-	-	3	5	7
Other	1	5	8	6	3
All Modes	261	181	267	155	114

Source: National Travel Surveys (DTLR, various years)

3.3.3.4 Time Spent Travelling

The average resident of the UK spent 360 hours travelling per year over 1998/2000 (Table 4.4; DTLR, 2001). This is compared to 70 hours travelling on foot. On average 1 hour a day was spent travelling, and on average 36 minutes were spent in the car and a further 12 minutes were spent walking.

The amount of time spent walking has been steadily falling over the years whilst the length of time spent in the car has been increasing. However, with average trip times for both modes combined remaining fairly consistent these changes reflect the falling distance people are walking.

3.3.3.5 Variations in Travel by Age and Sex

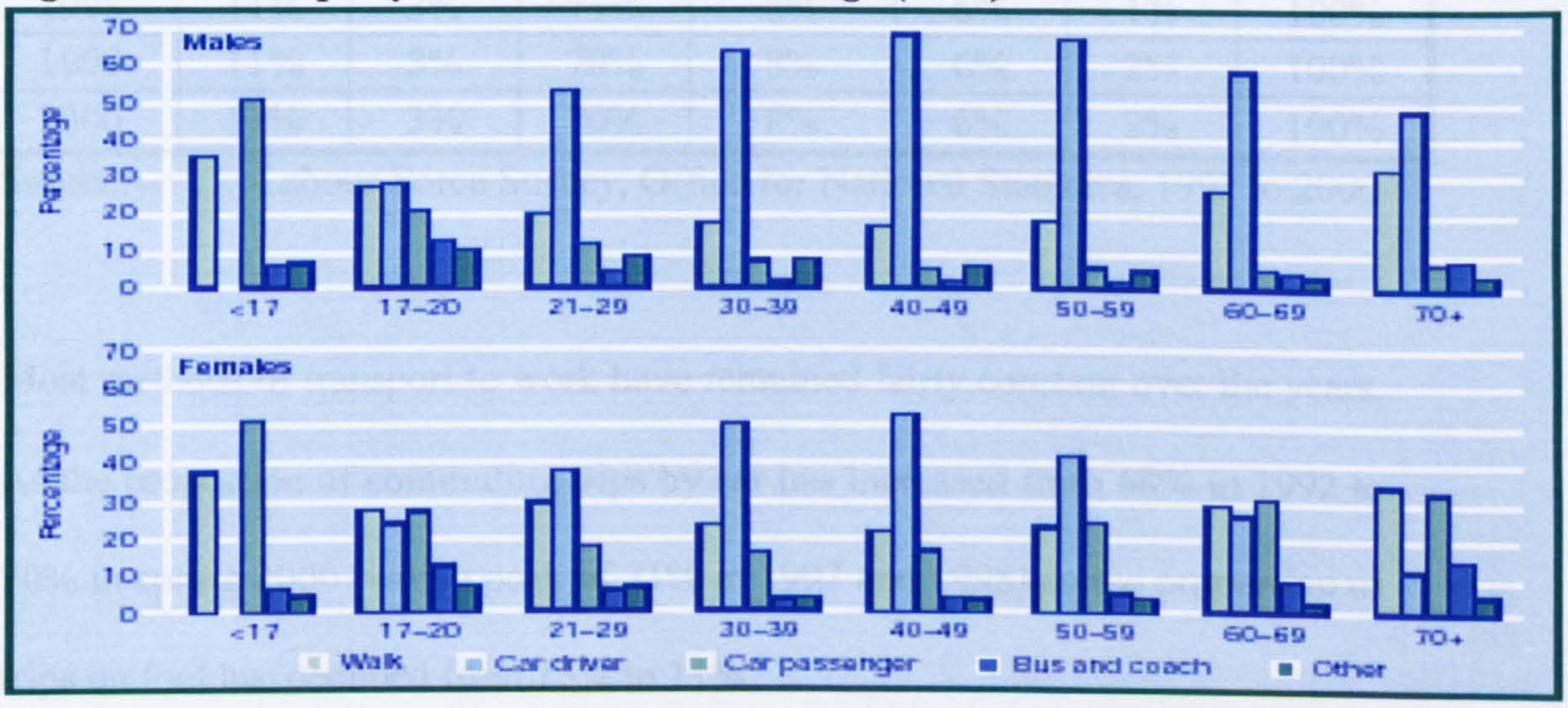
Men made an average of 1,041 trips per year in 1998/2000 compared with 1,020 trips made by women. However, in terms of walking trips, men made an average of 24 trips per year in 1998/2000 compared with 28 trips made by women. As age increased the numbers of trips made on foot by women increased whereas it decreased for men. There is a suggestion for a widening of the gap as age increases.

The average distance travelled per year by men was over 8,000 miles, almost two fifths further than women, who travelled 5,760 miles per year. In nearly all the different mode categories, men travelled further than women. The exception to this was walking, where women made on average 164 miles per year compared to 158 miles per year by men. As age increased the distance travelled on foot by women increased at a much higher rate than men.

Within this general pattern there are further marked contrasts between the sexes. Men make more of their trips by bicycle but less on foot than women. Over 1998/2000 this difference was most marked for people aged between 21 and 29. Men in this age band made 20% of trips on foot and 3% by bicycle whilst women in the same age band made 30% of trips on foot and only 1% by bicycle. For those under 21 and over 60 there was less of a difference in the proportion of trips by foot.

Figure 3.1 shows the variations of the main modes by age.

Figure 3.1: Trips by Main Mode, Sex and Age (2000)



Source: National Travel Surveys (DTLR, 2001)

3.3.4 Why do People Walk?

The reasons why people make walking trips, and the differences between different age groups and sexes is examined in this Section. Considered in the first part are the general trends. Some of the most important trip purposes of travel to work, to school and to the shops are the subject of the second part.

3.3.4.1 Travel to Work

The Labour Force Survey (ONS, 1992 to 2001) has asked questions on the usual mode of transport to work and the average time taken to travel to work each autumn quarter from 1992, and on the mode of travel only for each spring quarter from 2000. Table 3.4 gives a summary of the findings.

Table 3.4: Main Mode of Transport to Work and Mean Time Taken (1992–2000)

	Walk	Bicycle	Car	Bus/Coach	Rail	Other	All Modes
1992	13%	4%	68%	9%	6%	-	100%
1993	12%	4%	68%	9%	5%	2%	100%
1994	12%	4%	68%	9%	6%	1%	100%
1995	12%	4%	68%	8%	6%	2%	100%
1996	12%	4%	70%	8%	5%	1%	100%
1997	11%	4%	71%	8%	6%	-	100%
1998	11%	3%	71%	8%	6%	1%	100%
1999	11%	3%	70%	8%	6%	2%	100%
2000	11%	3%	70%	8%	6%	2%	100%

Source: Labour Force Survey, Office for National Statistics, 1992 to 2000

Most methods of transport to work have remained fairly constant over the years. As the proportion of commuting trips by car has increased from 68% in 1992 to 70% in spring 2000 (with a peak of 71% in 1997 and 1998) so the proportion of trips on foot has declined from 13% to 11%.

Other modes stayed pretty much the same. The average time to travel to work has shown a steady increase over the years from just over 23 minutes in 1992 and 1993 to over 25 minutes in 2000, a total of 8%.

3.3.4.2 Travel to School

There have been changes in school travel over the last 10 years. In 1989/1991 62% of primary aged children walked to school, but this had reduced to 54% by 1995/97. 1998/2000 has seen a slight increase to 56% of primary school children. The proportion of secondary aged children walking followed a similar pattern from 48% in 1989/91 to 42% in 1995/97 and 43% in 1998/2000.

The reduction in walking to school is associated with the increasing use of the car. Over the period 1989/91 to 1998/2000 the proportion of primary aged school children travelling to school by car increased from 27% to 36%. For secondary aged pupils the change was less, from 14 to 19%.

Pupils at secondary school travelled twice as far as those at primary school, 3.0 miles compared with 1.5 miles in 1998/2000. This helps to explain the differences in the mode of travel to school between these age groups. Only about one in ten primary school aged pupils travelled to school alone (e.g. with no other adult or child), but four out of ten secondary aged school children did so. Both of these percentages have reduced over the last 10 years.

3.3.4.3 Types of Shopping Trips

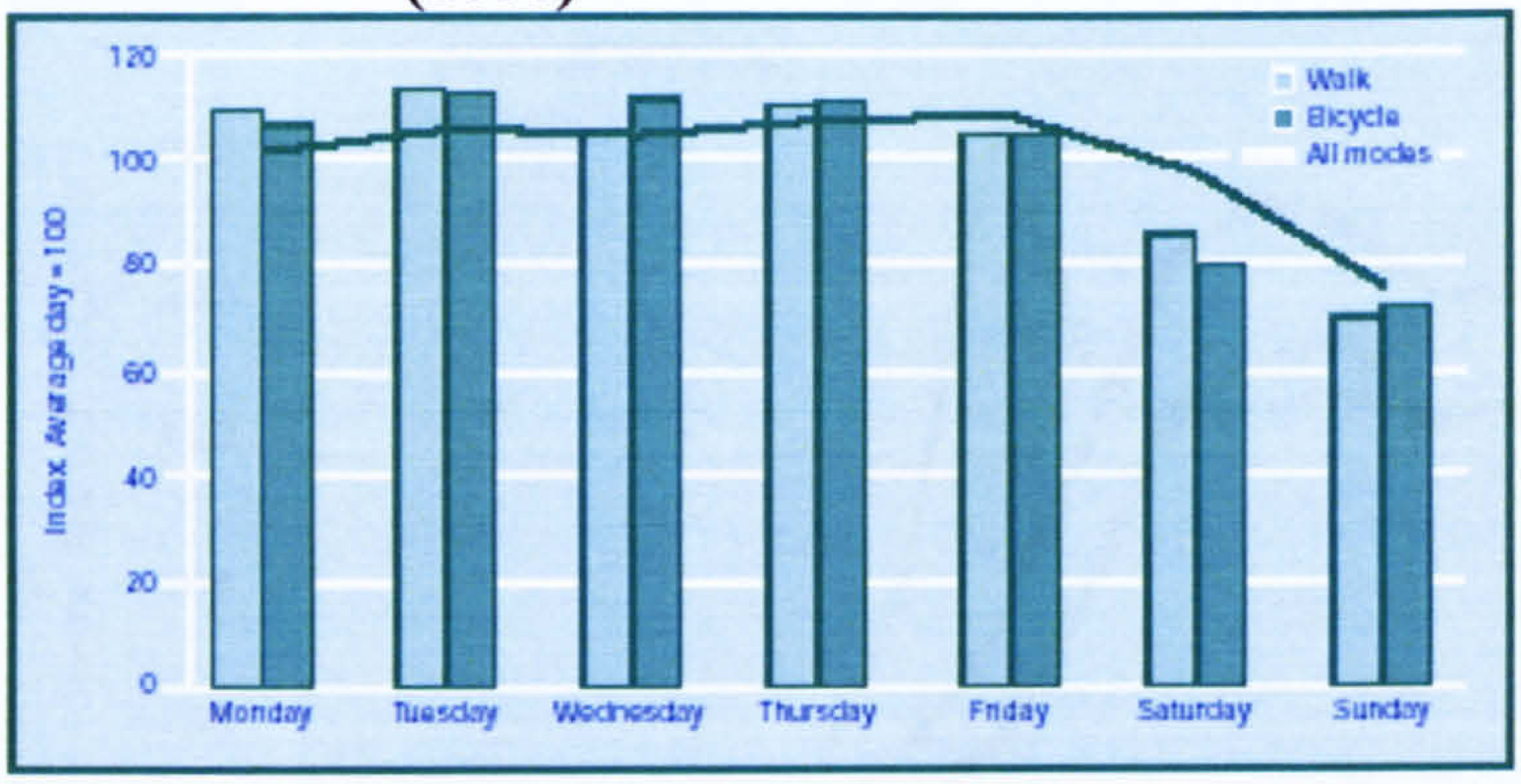
Since 1998 the National Travel Survey has been collecting separate data for food and for other shopping trips. Some summary results have been used to show changes in shopping trips made by foot. In 1998/2000 people made on average 216 shopping trips. Of these 55% were for food shopping and the remainder for other types of shopping. The most common mode of transport for food shopping was the car with 58%, however walking was the second most popular with 31% - more than all the other modes combined. The car was also the most common mode of travel for non-food shopping trips (62%), but again walking was the second most popular at 26%.

Not surprisingly, as the length of the shopping trip increases fewer people walked and more travelled by car and other motorised modes.

3.3.4.4 Daily Patterns of Travel

Using the NTS data, it is possible to determine how people travel at different times, by each mode of transport. Displayed in Figure 3.2 is the average proportion of trips made, expressed as a percentage of the modal split, throughout an average week, focusing on walking and cycling compared to all the modes of travel.

Figure 3.2: Average Daily Trips by Day of the Week and Mode (2000)



Source: National Travel Surveys (DTLR, 2001)

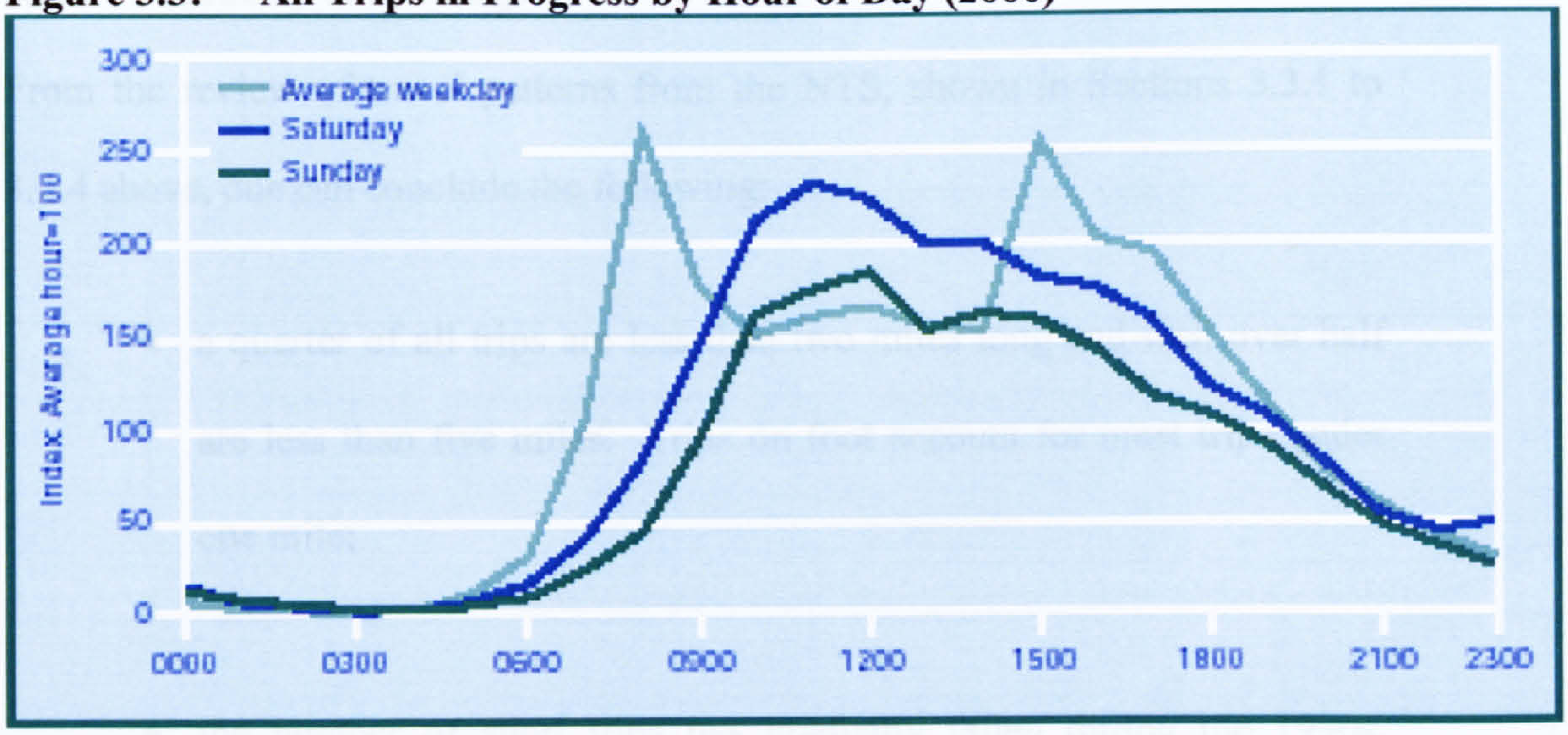
3.3.4.5 Hourly Patterns of Travel

Hourly patterns of travel have been analysed using 'trips in progress'. This variable is constructed by considering the start and end times of trips to determine whether a trip was in progress at a particular point in time. For the analysis used in this section sample points have been taken once every hour.

Table 7.11 on page 89 of DTLR (2001) displays the breakdown of trips in progress by time of day and mode of travel. On this basis, the peak time for travel across all modes is 0800 to 0859 on weekdays.

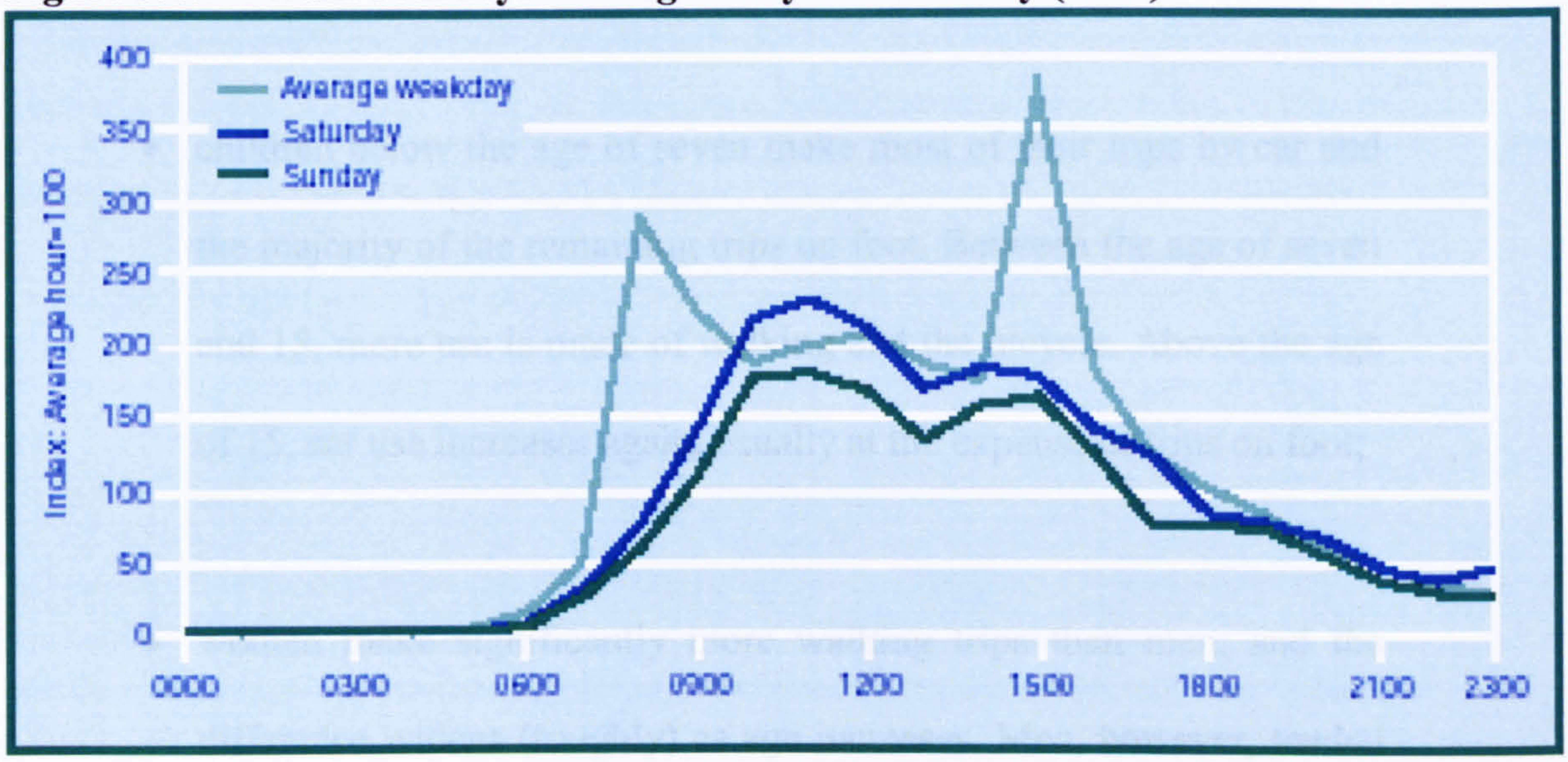
Comparing the average number of trips made by all the modes (Figure 3.3) against walking journeys (Figure 3.4), it can be seen that the two exhibit similar trip rates and frequencies throughout the day.

Figure 3.3: All Trips in Progress by Hour of Day (2000)



Source: National Travel Surveys (DTLR, 2001)

Figure 3.4: Walk Journeys in Progress by Hour of Day (2000)



Source: National Travel Surveys (DTLR, 2001)

The evening peak seems to be broader than that in the morning. This is partly due to the staggering of commuting and education trips that coincide in the morning. For both Saturday and Sunday, travel is spread more evenly throughout the day with travel peaking just before noon. Travel levels are lower on Sunday mornings than on any other day.

3.3.5 Summary of Findings

From the review of travel patterns from the NTS, shown in Sections 3.3.1 to 3.3.4 above, one can conclude the following:

- a quarter of all trips are less than two miles long and well over half are less than five miles. Trips on foot account for most trips under one mile;

- the number of short trips has gradually fallen during the 1990s, particularly those under a mile. This seems to have had an affect on the number of walking trips;

- children below the age of seven make most of their trips by car and the majority of the remaining trips on foot. Between the age of seven and 15, more use is made of walking and the bicycle. Above the age of 15, car use increases again, usually at the expense of trips on foot;

- women make significantly more walking trips than men, and the difference widens (roughly) as age increases. Men, however, tended to walk further;

- the car is not always the most common mode of travel. For shorter trips (especially under 1 mile) travel by foot is more common. Also, walking is usually part of the 'total journey', even when car or public transport is used as people usually walk to and from pick-up/drop-off points or parking sites;

- 11% of trips to work were on foot;

- 31% of food shopping trips were by walking and 26% of non-food shopping is made on foot (both the second most common mode, with car being the most popular over longer distances); and

- 56% of primary school aged children walked to school and 36% travelled by car. For secondary aged school children the corresponding figures were 43% and 19% respectively.

3.4 Discussion

The end of the 1990's were an important watershed in the UK in terms of transport policy and this has had an impact on the role that walking is expected to play in the economic and environmental well-being of the country.

There is renewed emphasis on encouraging greater use of walking, particularly as part of a move towards a more sustainable and integrated transport policy which recognises the environmental and social impacts of movement to a greater degree than in the past.

It is clear walking is an important mode of travel, which is often overlooked. The analysis of travel statistics shows there are falling trends for some trip purposes, but high levels or indeed growth in walking for others.

Where there is a decline in activity, the government is pursuing a pro-active agenda to reverse this by encouraging local authorities to pursue the enhancement or upgrade of existing pedestrian facilities and the development of new infrastructure aimed at encouraging a shift in modes from private motorised means of travel to walking (especially for short distance journeys). If this is to be achieved, one would expect there to be a need for robust means of assessing pedestrian facilities and infrastructure. This therefore suggests a need for a comprehensive understanding of the influences that affect walking including speeds, LOS's and other factors that affect people's decisions to walk.

In addition to developing policies for encouraging more people to walk rather than travel by car, the Government has published official forecasts to assist in identifying targets and for measuring the progress of its strategy. These have been published for England only but predict that the volume of walking trip-miles would increase by between 5% and 15% from 2000 to 2010 (10 Year Plan, DETR, 2000). Funding has been made available to implement new walking facilities or enhance existing infrastructure, and there is clear evidence that local authorities are now pursuing the Government's agenda (see for example Gaffron, 2002 and Spokes, 2003). However, despite the Government's attempts since the publication of the Transport White Papers in 1998, the observed data presented in this Chapter suggest a series of declining trends both in the numbers of walking trips and also the average distance travelled by walking. Table 3.1 in this Chapter shows that walking fell by 21% from 1990/1 to 1999/2000 while travel by car increased by 20% over this same period. This therefore raises a question over how the Government can reverse the observed trends and reach their aspirations.

If the Government's aims are to be achieved, one would expect there to be a need for a robust means of assessing pedestrian facilities and infrastructure. This therefore suggests there is a need for a comprehensive understanding of the influences that affect walking including speeds, LOS's and other factors that influence people's decisions to walk.

4 INITIAL ANALYSIS OF FACTORS AFFECTING WALKING SPEEDS: A PILOT STUDY IN EDINBURGH

4.1 Introduction

This Chapter is based on an initial analysis of walking speeds recorded at a pre-selected site in Edinburgh, Scotland. Walking speeds, flows, densities and other parameters were recorded to quantify the effects of different factors on pedestrian movements and identify variables which seem to exhibit a significant level of influence. The purpose of this Chapter is to:

- provide an indication of walking speeds and densities for observed levels of flows, and identify those factors that seem to significantly affect walking speeds;
- develop some statistical relationships between walking speed and various factors that might be considered to influence it, with a view to providing insights into the interactions between them; and
- give an indication of the form and quantity of information needed for the more detailed data collection and analysis exercise.

In order to do this, it was first necessary to research options for gathering the data and select the most appropriate for this study. The various options identified and the most suitable technique are described in the next Section.

4.2 Overview of Pedestrian Data Collection Techniques

4.2.1 Background

Over the years, there have been various pedestrian data collection techniques that have been developed and used by other pedestrian planners. The different options are reviewed in this Section, with a view to selecting the most suitable approach for this research. This has been done by comparing the advantages and disadvantages of each option.

4.2.2 Time-Lapse Photography

Time-lapse photography methods have been used to gather limited quantities of information from small physical areas where pedestrians are observed to walk. During the early days of pedestrian analysis, this technique was used to collect data for studies of pedestrian flows to establish relationships between speed and density for various categories of pedestrian movements. These include Older (1968), Navin and Wheeler (1969), and O'Flaherty and Parkinson (1972).

However, time-lapse photography usually involves a limited number of photographic images, and Turvey et al (1987) argued that its use can be problematic because of the small sample sizes of data it provides. In addition, Lovas (1994) confirmed this by carrying out tests of time-lapse photography surveys. He found that its main practical advantages are its ability to carry out a small-scale survey quickly, and its ease of administration and analysis.

However, the process is not as cheap as other methods which is one of the main reasons why only a limited number of pictures are taken thereby leading to a danger that the sample sizes of observations can be too low for investigations to be statistically significant. This was highlighted by Washington et al (2003), who emphasised the importance of large numbers of observations to ensure a more robust analysis.

Set out in Table 4.1 are the key advantages and disadvantages of time-lapse photography approaches, primarily based upon its use in past surveys.

Table 4.1: Advantages and Disadvantages of Time-Lapse Photography Techniques

Advantages	Disadvantages
Simple equipment needs	Limited numbers of photographs due to high cost of production
Provides easily comparable information about most observations	Due to high costs of photography processing, only small numbers of surveys are usually economic which can raise doubts over statistical confidence
Simple to administer surveys	Images might not be able to cover all viewing angles
	Many cameras needed to cover certain types of panoramic views

Source: based on Turvey et al (1987) and Lovas (1994)

Consequently, based on the above concerns, it was concluded that the time-lapse photography technique is not appropriate for this research.

4.2.3 Manual Pedestrian Data Collection Methods

Many pedestrian planners (e.g. London Underground Limited and York City Council) have used manual collection techniques for many years, to analyse speeds and densities. The process involves an enumerator carrying out 'observational' surveys (sometimes using hand held data loggers) over short time intervals (e.g. five minutes) to note the time taken to walk along a previously measured walking area. This is used to estimate the walking speed, and a second enumerator counts the total number of pedestrians entering and leaving the place of study. While this method has been extensively used in various studies, Turvey et al (1987) tested the process and showed there were significant drawbacks as shown in Table 4.2.

Table 4.2: Advantages and Disadvantages of Manual Data Collection

Advantages	Disadvantages
Simple equipment needs	Large propensity for error by the enumerators
Easy to administer	Only short time intervals can be surveyed because of the limitations of manual enumerators
Useful for 'spot counts' and short studies	Short periods of observations lead to small numbers of surveys which can raise doubts over statistical confidence
	Many observation sites needed to cover wide areas

Source: based on Turvey et al (1987) and Annesley et al (1989)

One of the critics of manual collection has been London Underground Limited who, as already mentioned above, have used the technique in the past to obtain data for their Station Planning Manual (1990), which was later repeated – again using manual techniques – in 1992 to recalibrate the Station Planning Manual (1993).

However, in their 1995 Annual Report, London Underground Limited stated they were unhappy with some of the results they had been receiving from their rolling programme of manual surveys and consequently would be changing their data collection method for their future versions of the Station Planning Manual to video surveys following the recommendations of their own checks. Therefore, based on the above reservations, it was concluded that manual data collection is not suitable for this research.

4.2.4 Digital Image Capture

Digital image capture involves using a form of video recording with specialised software which is capable of 'recognising' individual pedestrians, tracking them through a study area and noting their entry and exit times in the system. These times are then used to calculate walking speed. At the same time as the test subject is being tracked, a second imaging system notes the numbers of pedestrians in the study area, thereby giving the level of density. In principal, this process is exactly the same as all the other techniques, but the hardware tries to automate the steps. However, Daamen and Hoogendoorn (2003b) carried out a review of image sequence analysis techniques which have been used to perform pedestrian counting and pedestrian volume measurement. They identified a preferred system and tested the method to show it is capable of extracting pedestrian information, but acknowledged it had significant limitations, as shown in Table 4.3.

Table 4.3: Advantages and Disadvantages of Digital Image Capture

Advantages	Disadvantages
Permanent record of events is kept	Large propensity for error, which has raised doubts over confidence
Can cover wide panoramic views	Very high equipment costs
Useful for long periods of studies	Complicated laboratory equipment
Few observation sites needed to cover large study areas	Propensity to 'miss' a number of pedestrian subjects, and consequently needs many observation surveys to meet required number of sample data sizes
	Very complicated to administer
	Training or staff supervision required

Source: based on Daamen and Hoogendoorn (2003b)

Hence, based on the above concerns, it was concluded digital image recognition is not appropriate for this research.

4.2.5 Video Surveys

With the advent of widely available video recording and playback equipment in the 1980s, video recording of traffic and transport studies became increasingly popular. One of the earliest users were Polus et al (1983) who used slow motion video surveys to collect pedestrian data. Since then, the method has been widely used and described including Benz and Fruin (1984), Turvey et al (1991) and Reading et al (1995).

The concept involves recording pedestrian movements through the study area then playing the tapes back in the laboratory or office and extracting the data manually. The main features are summarised in Table 4.4.

Table 4.4: Advantages and Disadvantages of Video Surveys

Advantages	Disadvantages
More precise measurements of data can be obtained	Complicated laboratory equipment set-ups can be very costly
Permanent record of events is kept	Can take a significant amount of processing time, especially with large numbers of pedestrians
Can cover wide panoramic views	
Modern equipment has zoom, pause and on-screen timers for added benefits	
Can be very flexible	
Easy to administer	
Useful for long periods of studies	

Source: based on Benz and Fruin (1984), Turvey et al (1991) and Reading et al (1995)

Over the last decade, significant advances have been made in video technology, and it is now possible to carry out these types of surveys without the need for advanced digital recording equipment. A recent review has shown that, as a result of these technological enhancements, video surveys are now among the most widely used method for collecting pedestrian data (Zeeger et al, 1994).

4.2.6 Preferred Data Collection Technique

Based on the review of feasible options, video recording analysis was selected as the most appropriate method for collecting new data for this study. The following section will now explain the process adopted for this study.

4.3 New Data Collected

4.3.1 Data Collection Process

The process adopted for abstracting data for this initial analysis was the same technique used in many past studies by other researchers including Polus et al (1983), Ratnayake et al (1991), and Daamen and Hoogendoorn (2003a).

The concept involved marking out a rectangular box on the ground of known length and breadth, to calculate the area in which pedestrians walk through the system. An alternative to marking out the box on the ground is to mark the box on the video monitor screen, by approximating the dimensions using some of the physical features of the study site. The recorded videotapes of pedestrian movements were then played back, and data is abstracted using the following steps:

- Step 1 – select a random pedestrian about to enter the system and track them through the study area;
- Step 2 – note his or her entry and exit times in and out of the area;
- Step 3 – pedestrian walking time is thus obtained by subtracting the time of entry into the rectangular box from the time of exit;
- Step 4 – walking speed is then derived by dividing the known length of the box by the walking time, previously calculated in Step 3;
- Step 5 – rewind the tape back to when the test subject was in the middle of the rectangular box;
- Step 6 – as the selected pedestrian is in the middle of the study area, pause the tape and count the total numbers of pedestrians in the rectangular box with the selected subject;

- Step 7 – dividing the total number of pedestrians in the study site (obtained from Step 6) by the area of the rectangular box gives the density;
- Step 8 – the density (calculated in Step 7) will indicate which LOS threshold the system is currently operating under;
- Step 9 – record the other details of the pedestrian test subject (e.g. gender) as required from the data based on visual approximation; and
- Step 10 – go back to Step 1 and repeat the process, until the video tape is completely analysed or the required sample size is obtained.

There is nothing new in the above procedure, in that it has been applied and tested in many previous pedestrian surveys (for example Polus et al, 1983; Turvey et al, 1987; Annesley et al, 1989; Lam and Cheung, 2000; and Zacharias, 2000).

4.3.2 Site Selection and Survey Details

Four video surveys were carried out on four different days over the same stretch of walkway on Princes Street in Edinburgh, Scotland. This location was selected because it was one of the types of pedestrian areas the author wished to examine and also because of the readily available access to CCTV cameras made available by Edinburgh City Council. In order to obtain data for different walking conditions and LOS's, the same location was surveyed on different days and at different times. Details of the surveys are set out below:

- Survey 1 on Thursday Evening 25 March 1999 from 1600 to 1900 hours (a total of 3 hours);

- Survey 2 on Saturday Afternoon 27 March 1999 from 1400 to 1600 hours (a total of 2 hours);

- Survey 3 on Saturday Afternoon 22 December 2001 (the Pre-Christmas Saturday) from 1500 hours to 1600 hours (a total of 1 hour); and

- Survey 4 on Monday Afternoon 24 December 2001 (on Christmas Eve to catch last-minute shoppers) from 1500 hours to 1600 hours (a total of 1 hour).

These dates were selected to obtain data from high LOS ranges, especially the surveys prior to Christmas which produced heavy pedestrian flows. The analysis of the data from the first two surveys (Thursday evening and Saturday afternoon in 1999) showed that the walking conditions were representative of LOS ranges D and E, while the other two surveys (Saturday 22 and Monday 24 December 2001) gave LOS ranges E and F.

Based on the current practices identified in the literature review in Chapter Two, the following data about each pedestrian subject was collected:

- crossing time (sec);
- flow of pedestrians with the test subject;
- number of pedestrians in the box area when the test subject is in the middle (used to estimate density);
- whether the test subject is male or female;
- whether the test subject is an older person (assumed to be middle-aged and over, and was done by means of judgement); and
- whether the test subject is infirmed.

The data was entered into the SPSS computer database and statistical package to help with the analysis. The information was saved in individual files, with each record assigned a unique reference number. This allowed records to be combined and separated for multiple types of evaluations. Details of the walking environment (e.g. gradient, adjacent land-uses, etc) and other factors (e.g. age, etc) were also assigned to each record to allow various scenarios to be investigated in addition to time-trend analysis and geographical differentiations.

4.3.3 Statistical Characteristics of the Data

4.3.3.1 General Parameters

Tables 4.5 to 4.8 show the key characteristics of the data obtained from Data Sets 1 to 4. As can be seen, Data Set 1 (from Survey 1) has 313 observations, Data Set 2 (from Survey 2) has a sample of 421, Data Set 3 (from Survey 3) has 137 observations and Data Set 4 (from Survey 4) has 297 samples. The emphasis was to extract as many samples from the video surveys as possible, and the resultant total numbers of observations obtained from all 4 surveys was 1,017.

Table 4.5: Summary Statistics of the Data Set 1

	Crossing Time (sec)	No. of Peds	Average Two-Way Flow (ped/min/m)	Average Speed (m/s)	Average Space (m^2/ped)
N	313	313	313	313	313
Mean	6.052	7.410	32.124	1.117	2.673
Std. Error of Mean	0.045	0.041	0.092	0.009	0.016

Table 4.6: Summary Statistics of the Data Set 2

	Crossing Time (sec)	No. of Peds	Average Two-Way Flow (ped/min/m)	Average Speed (m/s)	Average Space (m^2/ped)
N	421	421	421	421	421
Mean	8.661	17.450	49.070	0.739	1.112
Std. Error of Mean	0.032	0.061	0.091	0.003	0.004

Table 4.7: Summary Statistics of the Data Set 3

	Crossing Time (sec)	No. of Peds	Average Two-Way Flow (ped/min/m)	Average Speed (m/s)	Average Space (m^2/ped)
N	137	137	137	137	137
Mean	9.909	40.311	57.791	0.661	0.497
Std. Error of Mean	0.057	0.331	0.191	0.005	0.004

Table 4.8: Summary Statistics of the Data Set 4

	Crossing Time (sec)	No. of Peds	Average Two-Way Flow (ped/min/m)	Average Speed (m/s)	Average Space (m^2/ped)
N	297	297	297	297	297
Mean	10.475	50.900	75.070	0.621	0.379
Std. Error of Mean	0.060	0.120	0.260	0.004	0.001

4.3.3.2 Distribution of Walking Speeds

Shown in Figures 4.1 to 4.4 are the distributions of walking speeds obtained from Data Sets 1 to 4. As can be seen, all appear uniform in shape with the exception of Data Set 2 (Figure 4.2) which has higher values of the frequencies over its middle range following the shape of a normal distribution.

Figure 4.1 Distribution of Walking Speeds from Data Set 1

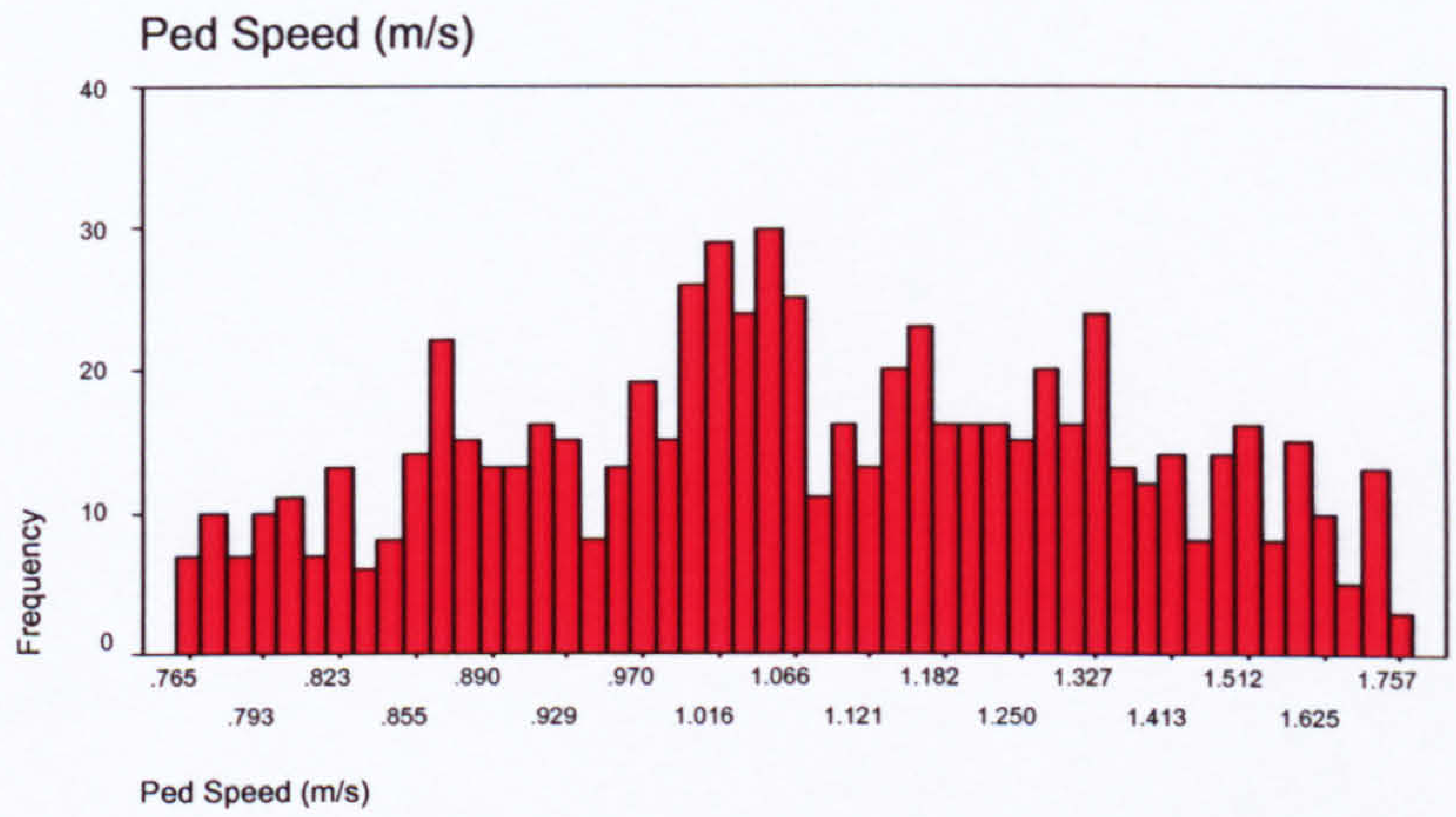


Figure 4.2 Distribution of Walking Speeds from Data Set 2

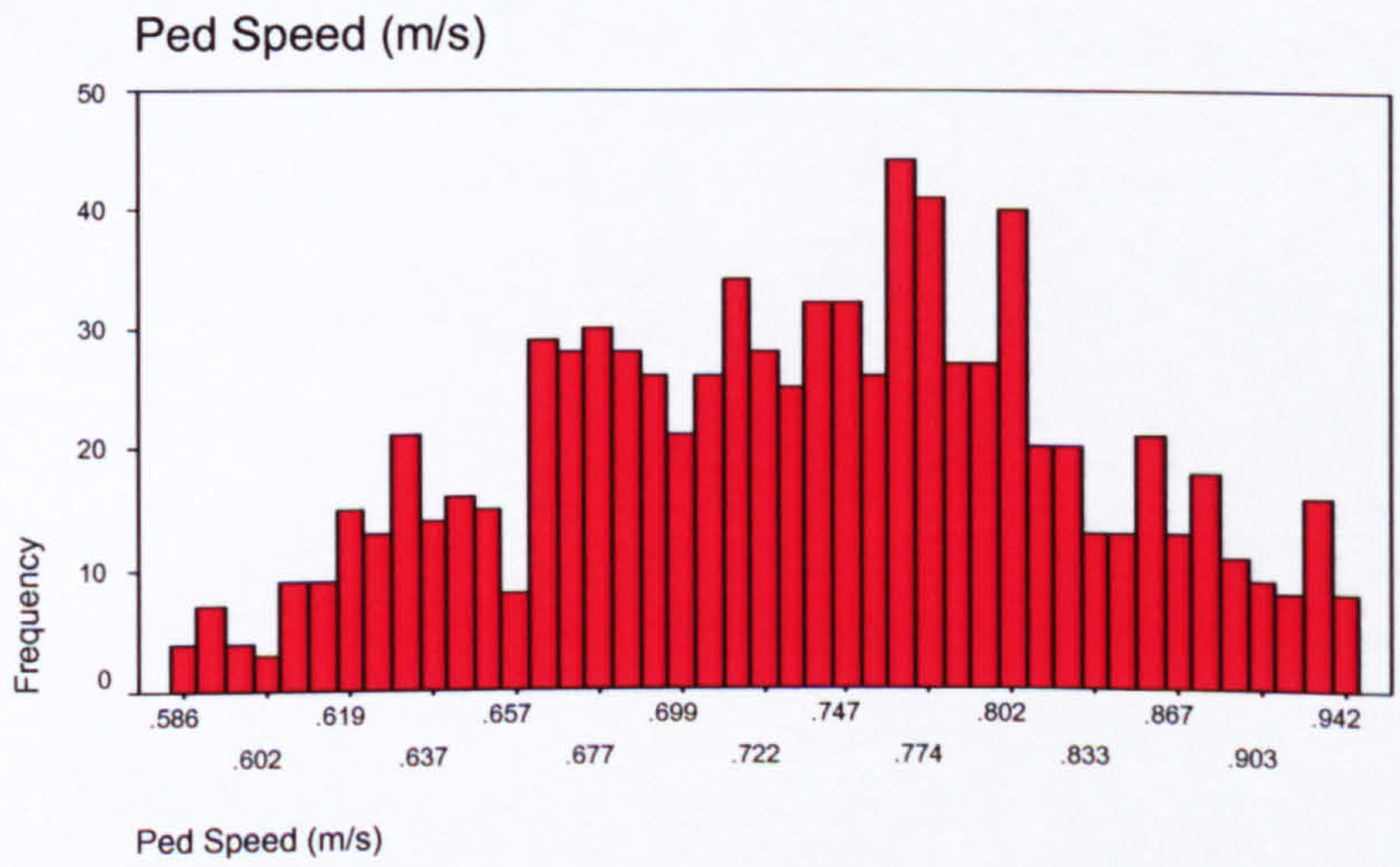


Figure 4.3 Distribution of Walking Speeds from Data Set 3

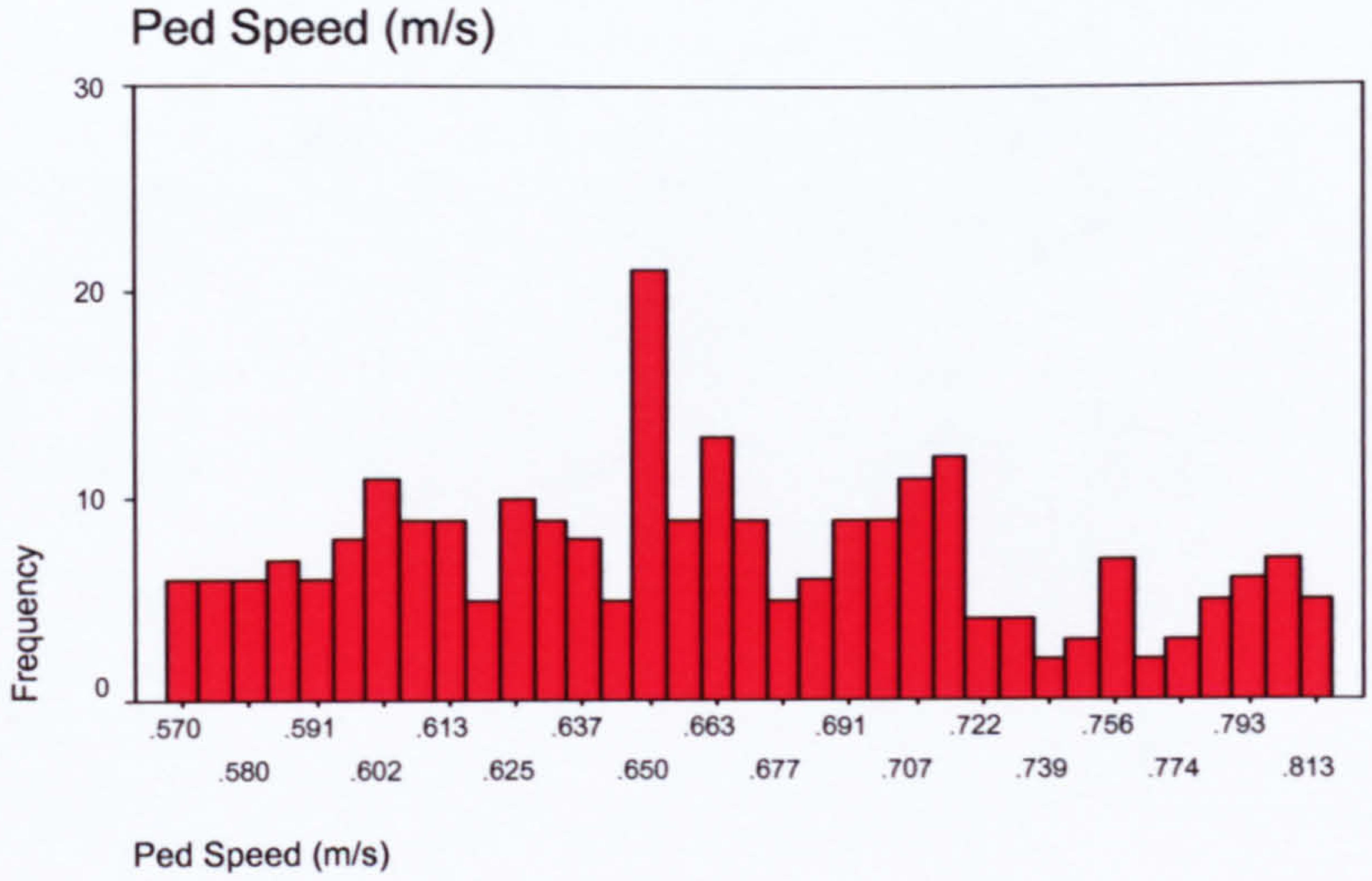
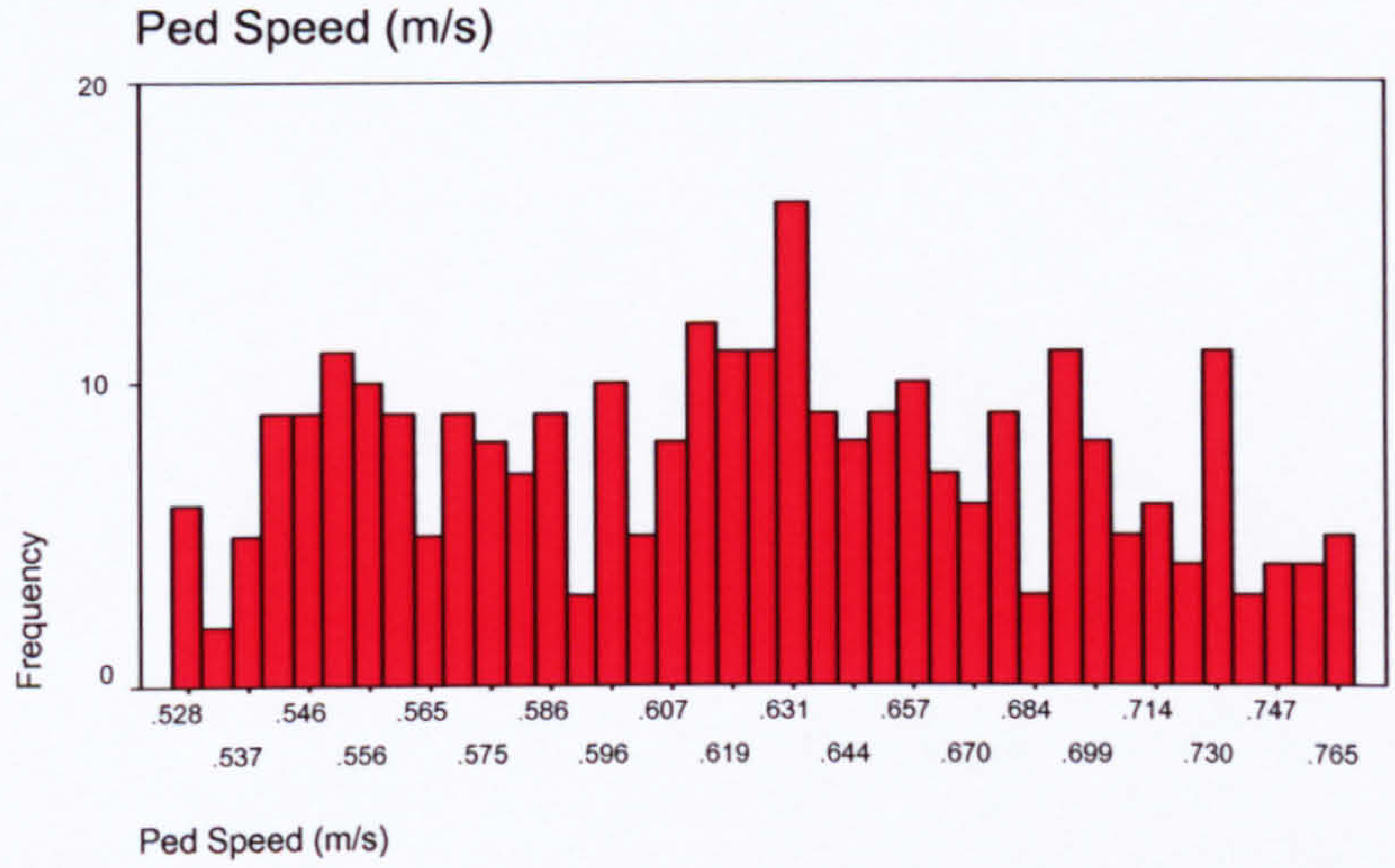


Figure 4.4 Distribution of Walking Speeds from Data Set 4



4.3.3.3 Proportions of Pedestrian Types

Summarised in Table 4.9 is a comparison of the other parameters obtained from all 4 data sets.

Table 4.9: Comparison of the Pedestrian Types and LOS Ranges

Parameter	Data Set 1	Data Set 2	Data Set 3	Data Set 4
Male	39.1%	38.0%	36.5%	40.5%
Female	60.9%	62.0%	63.5%	59.5%
Young	65.8%	66.1%	68.0%	60.7%
Older	34.2%	33.9%	32.0%	39.3%
Infirm	1.1%	1.5%	0.5%	0.7%
LOS Range	D	E	E	F

The LOS's ranged from D to F, with an average for all the data combined of LOS Range D. The definition of LOS was based on flow and there could be small differences in the classification if speed or pedestrian space was used.

As can be seen, the ratio of male subjects varies from 36.5% to 40.5%, and the proportion of female ranges from 59.5% to 63.5%. The percentage of older people varies from 32.0% to 39.3% - quite a large variation compared to some of the others. The proportion of infirm pedestrians ranged from 0.5% to 1.5%. Given the characteristics of the walking area surveyed, namely a popular retail street, and the times of the observations, at periods frequented by shoppers, it was not surprising to see such a high proportion of female pedestrians, given that national travel patterns show that shopping is predominantly undertaken by women, who usually have the majority of domestic duties (DTLR, 2001).

Another common perception is that shopping is a group or family activity. Unfortunately the process of abstracting the data from the video tapes used did not differentiate between pedestrians who walk alone or as part of a group, and therefore this could not be explored in this pilot case study. In addition, the two-tier banding of age did not highlight any variations in walking speeds by age. It was therefore decided that for the detailed analysis, data from the video tapes would be re-abstracted with the inclusion of more pedestrian characteristics including walking alone or part of a group and the disaggregate of age into more groups, as suggested by the literature review in Chapter Two. The final list of data variables and how they were identified is described in the Research Methodology in Chapter Five.

4.4 Statistical Analysis

4.4.1 Tests to Determine Whether the Speed Distributions are Skewed

Before undertaking any statistical analysis, a test was carried out to check if pedestrian speeds were skewed. All the data sets were found to have skewed speeds, and the natural logarithm of the walking speed was computed in an attempt to derive a more normal shape of distribution. This was considered to be more suitable for conducting t-tests (Washington et al, 2003). Therefore, the log of speed was used for the remaining analysis.

4.4.2 Speed versus Flow and Density

4.4.2.1 Overview

A series of statistical relationships were developed based on the recommended HCM methodology (TRB, 2000). The HCM methodology estimates flow using speed and pedestrian space (the reciprocal of density) as follows:

$$V = S / M$$

where: V = flow or volume;

S = speed; and

M = pedestrian area module ("space") = 1/density.

This relationship can be re-arranged as follows:

$$V = S \times D$$

$$\Rightarrow \quad S = V / D$$

$$\Rightarrow \quad \text{Ln } S = \text{Ln } V - \text{Ln } D$$

where: D = density; and

Ln = the natural logarithm.

To identify differences between the LOS ranges, separate statistical relationships using the HCM methodology were developed for each data set. To examine whether increasing the sample size improves the predictive power of the statistical relationship all the data was combined into one large data set and a fifth statistical relationship was developed using the combined data. To allow for some validation of the resultant relationships from the HCM methodology only 80% of the aggregated data was used to develop the relationships and 20% was used as a hold-out sample for testing the relationships.

The statistical relationships developed using the HCM methodology are shown in Appendix One. These relationships were developed separately for Data Sets 1 to 4 and for all the data combined, to allow for an increased sample size. The best-fit relationship obtained was from the statistical relationships developed using all the data combined and is set out below.

4.4.2.2 Best-fit HCM Relationship

The statistical relationship developed using the HCM methodology with all the data combined is shown in Table 4.10.

Table 4.10: Best-fit HCM Relationship developed from Pilot Study

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	LNDEN	-.263	.006	-.566	-44.709	.000
	LNFLOW	6.29E-02	.001	.716	56.555	.000

a. Dependent Variable: LN_SPEED

b. Linear Regression through the Origin

Both variables used (total two-way flow and density) were found to be statistically significant at the 95% Confidence Level. The parameter LNDEN (the natural logarithm of density) is also right-signed suggesting the relationship is as one would expect. However, the HCM methodology only provided an adjusted R-square value of 59%, suggesting it is only accounting for just over half of the variation in pedestrian speed. Estimates using the 20% hold out sample gave a Pearson correlation coefficient between the predicted and observed of 0.52 and the mean absolute percentage error (MAPE) is 37.5%.

4.4.3 Other Statistical Tests

In order to identify whether the other variables collected might influence walking speed, a series of t-tests were undertaken at the 5% level. The analysis was also undertaken for each data set separately and then using all the data combined. The results are presented in Table 4.11 below.

Table 4.11: Results of T-Tests on Parameters

Data Set	Flow	Density	Gender	Age	Infirm
1	Sig.	Sig.	Not Sig.	Sig.	-
2	Sig.	Sig.	Not Sig.	Sig.	-
3	Sig.	Sig.	Not Sig.	Sig.	-
4	Sig.	Sig.	Not Sig.	Sig.	-
All Data	Sig.	Sig.	Not Sig.	Sig.	Sig.

Sig. = variable was found to be significant
Not Sig. = variable was not found to be significant

The sample sizes for observed infirm pedestrians were considered to be too small and therefore inappropriate for use in analysing the data sets separately, but when they were combined they gave a much better sample. Therefore, the analysis on whether being infirmed affects walking speed was carried out for all 4 data sets combined together.

As can be seen, the above analysis suggests that other factors (e.g age, physical fitness) do have a statistically significant affect on walking speeds as initially thought. The exception to this, however, was gender but this could be due to the low sample sizes.

4.5 Summary of Findings

What is striking from the analysis undertaken is that the statistical relationships developed and presented above in Section 4.4.2 only seem to account for a small proportion of the variation in pedestrian speed and leave a lot unexplained. The best performing relationship was obtained by combining all the data together, but even then the model only accounted for just over half of the variations in the results. However, according to the findings of the literature review, these parameters are the main variables used in pedestrian modelling studies.

When the data was analysed based on the LOS range the best performing model came from Data Set 1 (see Appendix One). This is likely to be because this data was collected in conditions of relatively low flows (LOS Range D, the lowest of all the data sets) where one would expect to find flow and therefore density to be the main determinants of walking speed since there are few other constraints being imposed on pedestrians in these conditions. It is, therefore, the author's belief that these variables on their own do not include enough other factors to provide a reasonable description of walking speeds, especially when other constraints are imposed on pedestrians. This was also confirmed by the findings of the other statistical tests shown in Section 4.4.3 which showed that other factors (e.g age, physical fitness, etc) do have a statistically significant affect on walking speeds as initially thought.

One can conclude it is worthwhile incorporating other factors into the statistical analysis to test whether their inclusion would improve the predictive performance. Also, there is perhaps a need to investigate other model structures. This is the main finding from this initial analysis of those variables and factors identified as influencing walking speeds. The next Chapter will set out a series of hypotheses to test the theory and describe the research method to undertake the detailed analysis.

5 HYPOTHESIS DEVELOPMENT AND RESEARCH METHOD

5.1 Introduction

Described in the first half of this thesis were the current techniques used by transport planners and engineers for modelling pedestrian movements, the importance of walking as a mode of travel and hence the need for accurate and robust methods for planning and designing walking facilities, and how well existing procedures perform with real data. The initial findings suggest better predictive models are required.

Consequently, a series of Research Hypotheses were developed to test some of the propositions identified earlier. These will be pursued in a clear and systematic Research Method set out below.

5.2 Selected Areas of Research

5.2.1 Summary of Findings

Before identifying the areas of research, it is worth summarising the findings of this study so far, in order to set the scene for the rest of this investigation:

1. only certain LOS ranges (often quite low levels of pedestrian density) have been developed using actual measured data. The LOS ranges of other (often the denser) walking conditions have been developed by extrapolation or similar methods;

2 although there has been some research into relationships for different types of pedestrian environments, this seems to have been carried out using limited amounts of data. This has included manual data collection systems which often involve small periods of 'spot counts'. This often results in models being developed using small samples of data which are not as statistically robust as those with larger sets of data;

3 in the main, pedestrian planning studies use a standard relationship of walking speeds for all types of pedestrians. The first half of this thesis suggests there is a need for a series of disaggregated relationships which include the effects of various different types of pedestrians and walking environments. The findings of the analysis undertaken in the previous Chapters of this research would suggest a need for walking speed relationships with the following disaggregation:

- pedestrians separated by gender;
- pedestrians defined by age;
- whether pedestrians carry bags or luggage;
- distinguish between those who walk alone and those in groups; and
- incorporate the characteristics of the surrounding environment and conditions.

5.2.2 Research Objectives

Before identifying the areas of research, it is worth remembering the main objectives of this study so as to relate them to the investigation. There are six main aims for this thesis, namely:

1. review current practices and procedures for modelling pedestrian movements;

2. identify the factors and variables used in current modelling processes and test their goodness-of-fit using independent data;

3. determine other factors which have a significant affect on the walking speeds of pedestrians in certain types of walking environments and conditions;

4. attempt to develop statistical relationships which can be used by transport planners to model the interactions between these factors and walking speeds, and thereby assist transport planners with the study and design of suitable pedestrian facilities;

5. test and validate the statistical relationships developed; and

6. identify and discuss future areas of research.

Therefore, the following research hypotheses have been developed to address these overall objectives.

5.3 Identified Research Hypothesis

5.3.1 Background

From an assessment of the above, a set of research hypotheses was identified for testing. These are described below.

5.3.2 Testing LOS Ranges Developed from Past Studies

It was shown in Chapter Two that only certain on-street LOS ranges have been developed using actual measured data, with other (denser) LOS ranges developed by extrapolating from the lower LOS ranges. Where research has been carried out on denser LOS limits, this has usually been in extremely confined walking environments such as underground station connections.

The lack of research on denser LOS ranges in on-street locations is primarily due to a lack of sufficient data, and raises difficulty in assessing busy shopping streets or Central Business Districts (CBD's). This relates to the first objective of this research. In addition, since the publication of the transport White Papers, the policy review in Chapter Three showed that there has been a considerable increase in activities by Local Authorities in developing pedestrianised areas and therefore an argument exists for looking at denser LOS ranges to help study pedestrian movements in facilities which are capable of accommodating the projected increase in pedestrian flows. Consequently, two hypotheses have been identified with the overall aim of producing a better understanding of the impacts of denser LOS ranges. They are as follows:

Hypothesis One: *Average walking speeds in denser LOS ranges (e.g. E and F) for on-street shopping areas will be lower than the average values documented in the HCM planning guidelines.*

Hypothesis Two: *Some of the average walking speed results for the low and medium LOS ranges (e.g. A to D) identified by this research will be reasonably close to those produced from past work using similar LOS data and analysis techniques, and incorporated in the HCM.*

The first hypothesis above is designed to establish the degree of variation from the current 'industry-standard' averages used for design guidance, by comparing against actual measurements from data collected in this research. The published literature and data on this topic, as discussed in Chapter Two, seems to have neglected these denser LOS ranges to a certain degree. This could be as a result of its low importance to the majority of planners when compared with other issues, but it has been argued there is a growing need for more robust estimates of walking speeds in LOS ranges E and F (Still, 2000). The second hypothesis is intended as a check of the findings of this study.

5.3.3 Identify which Pedestrians Characteristics and Environmental Factors have a Significant Influence on Walking Speeds

The hypotheses in this section relate to the second research objective and are intended to identify some of the specific pedestrian characteristics and some of the environmental features which have a significant impact on walking speeds. Four hypotheses were identified, as follows:

> *Hypothesis Three:* *Some of the different characteristics of a pedestrian (e.g. age, gender, whether they are carrying baggage) will significantly slow walking speed.*
>
> *Hypothesis Four:* *Walking in groups of two or more pedestrians will significantly slow walking speed.*
>
> *Hypothesis Five:* *Walking speeds are significantly slowed by certain physical geometric layout factors (e.g. walkway gradient, width, proximity of road junctions).*
>
> *Hypothesis Six:* *Pedestrian walking speeds are significantly different at different time periods of the day.*

From Chapter Two, one can conclude that current practice is to use the same average relationships of walking speeds for all types of pedestrians. This is the same as assuming different types of pedestrians do not have distinct walking characteristics.

Little attention has been devoted to developing an understanding of how these walking features differ between groups of pedestrian types, and the impacts that these have on speeds. The four hypothesis described above have been developed to assist in identifying some of the variables which should be explored in the development of the statistical relationships to try and explain the affects and interactions of these factors on walking speeds.

5.3.4 Assessing the Effects of Different Pedestrian Environments on Walking Speeds

Following on from the analysis of the variations of current LOS ranges, the next hypothesis primarily relates to the third main research objective, and is intended to help identify how various pedestrian walking environments (and their associated characteristics) affect pedestrian walking speeds. One hypothesis has been identified in this section, as follows:

> *Hypothesis Seven:* *Pedestrian speeds are significantly different in different walking environments (e.g. walkways next to office buildings, retail shops) and weather conditions (e.g. rain, winter).*

Examination of this hypothesis will help identify the scale of variations in the values, and will give an approximation of the potential errors incorporated in the existing criteria.

5.4 Research Method

5.4.1 Background

Having defined the research hypotheses to be tested, analysed and discussed in this thesis, a suitable research method is developed in this section.

5.4.2 Overview of Data Collection Process

The general aim of this research is to gain a more comprehensive understanding of the interactions between various types of pedestrian and walking environments. The literature review showed that current relationships of walking speeds are based on aggregated data and potentially mask the key effects individual factors could make. However, when these aggregated data variables are tested in the initial analysis (pilot study) presented in Chapter Four they did not produce very good models. Certainly, there is a strong suggestion that more disaggregated data variables would provide better models. Therefore, it was decided to gather new data on walking movements, with the characteristics of the pedestrian, the walking environment and the travelling conditions broken down into many different factors which are perceived to have a potential influence on walking speeds. The data required was identified from a step-by-step process, as follows:

- step 1 – identify an initial list of data needed;
- step 2 – compare against the aims of the research;
- step 3 – check against the findings from the past studies and literature review; and
- step 4 – amend the data needs according to outcomes from steps 2 and 3 above.

It was believed prudent to gather as much data as possible and that too much was better than too little. The above process produced a final list of detailed data needs, which are set out below.

5.4.3 Description of the Variables Identified for use in the Analysis

This Section describes the variables identified as being required for collection for use in the study of factors effecting pedestrian walking speeds and the development of statistical relationships to model their interactions.

The potential explanation variables to improve on the existing pedestrian models were selected on the basis of those used currently in the HCM model and those which were either in the control or outwith the control of the designer. This was supported by the findings of the literature review described in Chapter Two and the results of the initial analysis (pilot study) shown in Chapter Four.

The following sections include a description of each variable identified, presented in a series of tables to aid understanding, along with the reasons for their selection.

5.4.3.1 Variables Used in the Existing Highway Capacity Manual (HCM) Methodology (normally in the control of the designer)

Table 5.1 below sets out the variables required for reproducing the HCM methodology and also provides a brief definition of each variable.

Table 5.1: Existing Highway Capacity Manual Model (HCM) Variables

Variable	Unit	Definition	Expected Effect on Speed
Time	Seconds	The time taken by the randomly selected pedestrian to walk through the length of the observation area	N/A
Peds_Centre	Number of Pedestrians	The number of pedestrians observed in the study area when the randomly selected pedestrian is in the centre of the rectangle/box observation area	Large Negative
Flow_With	Number of Pedestrians	The flow of pedestrians in the same direction as the randomly selected pedestrian, during the time he or she takes to walk the length of the rectangle/box	Large Negative
Flow_Against	Number of Pedestrians	The flow of pedestrians in the opposite direction as the randomly selected pedestrian, during the time he or she takes to walk the length of the rectangle/box	Large Negative
Speed	Metres per Second	The estimated speed of the randomly selected pedestrian, obtained by dividing the length of the rectangle/box by the observed walking time. Speed is used as the dependent variable	N/A
Den_Centre	Pedestrians/m^2	The pedestrian density estimated by dividing the number of pedestrians in the centre of the rectangle/box (variable 2 above) by the area of the rectangle/box	Large Negative

5.4.3.2 Additional Variables in the Control of the Designer or Planner

The literature review found geometric layout of a walkway can significantly affect walking speeds, but what was surprising was the wide range of factors identified; this was more than those factors used in the HCM. Most of these variables are in the direct control of the transport planner and are easily measured. It is not unreasonable to include them in any potential new model which will improve the accuracy of the analysis and provide a more holistic insight into the study and design process. Based on the literature review the variables in Table 5.2 were selected for analysis. The table also shows the names used to describe them, along with brief definitions.

Table 5.2: Additional Variables in Control of the Designer or Planner

Variable	Unit	Definition	Expected Effect on Speed
Gradient	Percent	The gradient of the walkway expressed as a percentage. Positive for uphill and negative for downhill	Large Negative
Guard_Rail	1 or 0	1 if there is a continuous pedestrian guard rail along the length of the walkway, but outside the observation area, otherwise 0	Slight Negative
Furniture	1 or 0	1 if there was any street furniture intruding pedestrian flow or was within the observational area, otherwise 0	Slight Negative
Entrance_Exit	1 or 0	1 if there were any entrances or exits to adjacent land-uses within 1m of the observational area, otherwise 0	Slight Negative
Shopping_Area	1 or 0	1 if the site was within a shopping street environment, otherwise 0	Negative
Residential_Area	1 or 0	1 if the site was within a residential street environment, otherwise 0	Slight Positive
CBD_Area	1 or 0	1 if the site was within a CBD area, otherwise 0	Large Positive
Junction	1 or 0	1 if there was a junction or crossing within 10m of the observational area, otherwise 0	Large Negative
Bus_Stop	1 or 0	1 if there was a bus stop within 1m of the observational area, otherwise 0	Negative
Bus_Lane	1 or 0	1 if there was a bus lane adjacent to the walkway observational area, otherwise 0	Negative

5.4.3.3 Variables Relating to Pedestrian Characteristics (Not Normally in the Control of the Designer)

The characteristics of pedestrians were also shown to potentially influence walking speeds by the literature review. Therefore, for the individuals followed through the rectangle/box area, the categories presented in Table 5.3 were made, based on the findings of the literature review. Clearly all of these factors are not within the control of the transport planner or designer, but it is still useful to see how much influence they would have on any new models developed.

In particular, the age of the pedestrian was found to potentially influence walking speeds. Many studies have shown age to be a major contributory factor (e.g. Murray, 1986; Knoblauch et al, 1995; and Edlmann and Pitcairn, 2000). Specifically, Edlmann and Pitcairn (2000) showed speeds can be affected across a wide range of ages and suggested analysis should take account of age groups disaggregated into 4 groups consisting of children, young adults, medium-aged adults and the elderly. This could allow planners to design for areas where children frequent more than other types of pedestrians or where it is necessary to plan for older people. Therefore, the age of the pedestrian was categorised into these 4 groups with child defined as being any pedestrian who was inspected as being of an age up to their late teens, a young adult defined as being any pedestrian examined as being of an age up to their late thirties, a medium-aged adult defined as being any pedestrian examined as being of an age up to their late 50's, and an elderly pedestrian defined as being someone over their late 50's.

Coding of the data was by visual inspection and there were inherent difficulties in interpreting some of the data. For example, the age categorisation is based on the researcher's judgement and clearly the precision at the boundaries is dubious. It is acknowledged that this might be a weakness or might have incorporated biases in the data, but the intention was to gather large sample sizes which should minimise any potential negative effects of this. Further details of the sample sizes of the data collected are shown later in this Chapter and in Chapter Six.

Table 5.3: Variables Relating to Pedestrian Characteristics

Variable	Unit	Definition	Expected Effect on Speed
Gender	1 or 0	The gender of the test subject (1 = male, 0 = female)	Positive
Child	1 or 0	1 for a pedestrian who was visually inspected as being up to their late teens in age, otherwise 0	Positive
Young_Age	2 or 0	2 for a pedestrian who was visually inspected as being up to their late thirties in age, otherwise 0	Large Positive
Medium_Age	3 or 0	3 for a pedestrian who was visually inspected as being up to their late 50's in age, otherwise 0	Negative
Elderly	4 or 0	4 for a pedestrian who was visually inspected as being over their late 50's in age, otherwise 0	Large Negative
Infirm	1 or 0	1 for an infirmed pedestrian, otherwise 0. Being infirmed was defined as walking with a limp or with an aid and was collected by visual inspection.	Large Negative
Bags	1 or 0	1 for a pedestrian carrying baggage/luggage, otherwise 0. This was based on visual inspection and does not include details of the baggage weight, size or number being carried	Negative
Stops	Number	This is the number of stops made by a pedestrian as they walk through the observation area. A stop was recorded when the pedestrian made a complete stand-still for whatever reason including stopping to look into a shop window, read a sign or any other reason	Negative
Child_Animal	Number	The number of animals on a lease or children accompanying the observed pedestrian	Negative
Group	1 or 0	1 if the observed pedestrian is walking as part of a group of 2 or more people, otherwise 0	Negative
Deviate	1 or 0	1 if the observed pedestrian makes a deviation from walking in a straight line through the rectangle/box, otherwise 0. A deviation was recorded when the observed pedestrian moved at an angle away from the straight line to avoid oncoming pedestrians, to overtake other pedestrians or for any other reason	Negative

5.4.3.4 Variables Related to Adjacent Land-Use (Not Normally in the Control of the Designer)

The literature review showed that walking speeds vary in different pedestrian environments, suggesting different land-uses adjacent to the walkway could be influential. In addition, pedestrian behaviour can be affected by the presence of motorised traffic flows on roads adjacent to the walkway and on-street parking. Therefore, it was decided to include the variables in Table 5.4.

Table 5.4: Variables Related to Adjacent Land-Use

Variable	Unit	Definition	Expected Effect on Speed
Retail	1 or 0	1 if there are any retail units/shops within 10m of the observational area, otherwise 0	Negative
Houses	1 or 0	1 if there are any houses/domestic dwellings within 10m of the observational area, otherwise 0	Positive
Offices	1 or 0	1 if there are any offices/businesses within 10m of the observational area, otherwise 0	Large Positive
Vehicles	1 or 0	1 if there is a flow of vehicular traffic within 10m of the observational area, otherwise 0	Negative
Parking	1 or 0	1 if there are any vehicles parked within 10m of the observational area, otherwise 0	Negative

5.4.3.5 Variables Related to the Time and the Environment (Not Normally in the Control of the Designer)

In addition to the variables describing the characteristics of the pedestrians, the literature review found other factors describing the built and natural environment and also the time of travel can influence walking speed but are also outside the control of the transport planner or designer. To examine how much of an influence they have the variables in Table 5.5 were included.

These variables would help examine the effects of walking in winter (defined as being between the months of November and February, inclusive) against other months, under different weather conditions (categorised between rain and non-rain), walking on a weekday as opposed to a weekend, and travelling during the times of commuter travelling (defined as between 0800 to 0900 hours or 1700 to 1800 hours based on the analysis of travel patterns shown in Chapter Three) versus non-commuter times.

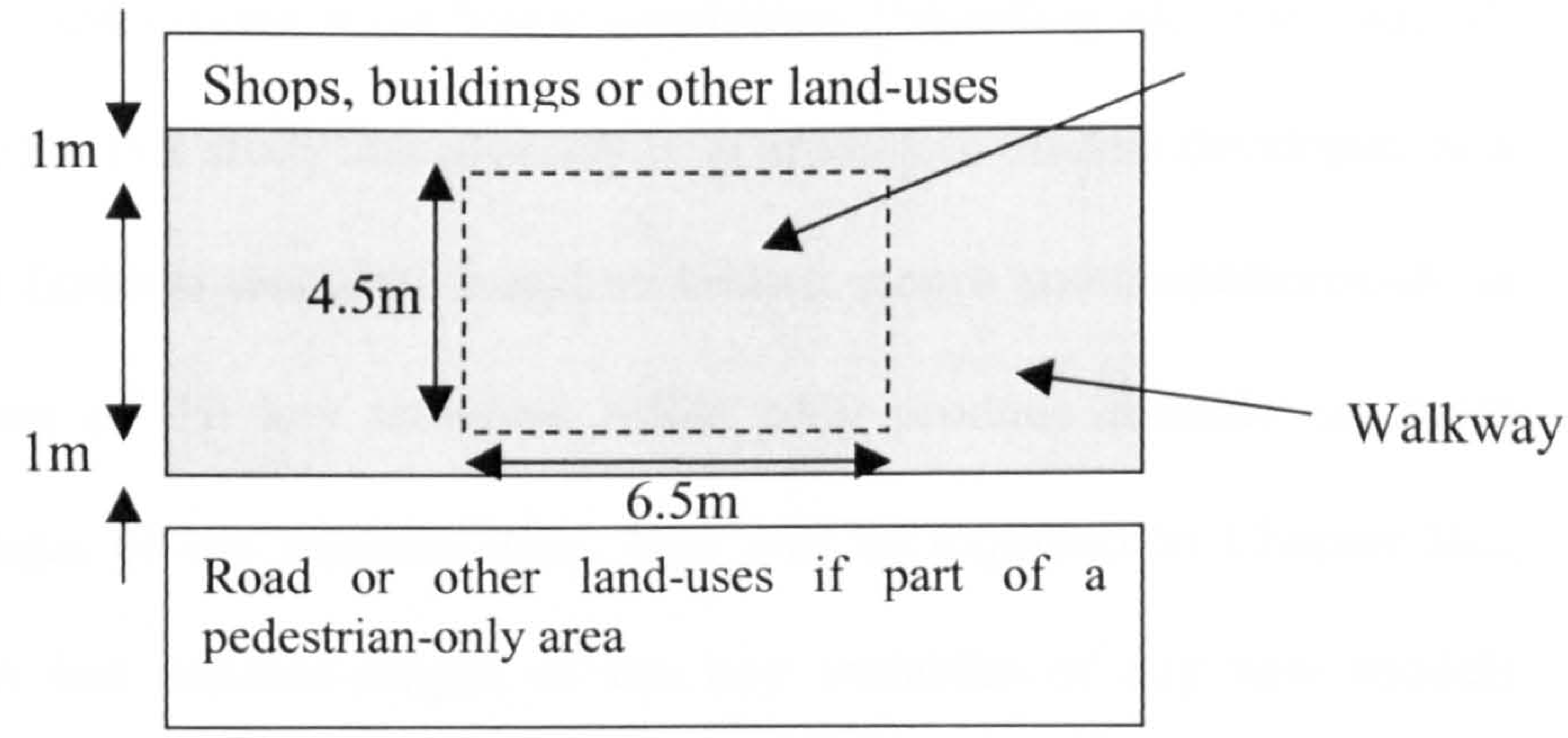
Table 5.5: Variables Related to the Time and the Environment

Variable	Unit	Definition	Expected Effect on Speed
Winter	1 or 0	1 if the observed pedestrian was recorded as walking during a winter month, otherwise 0. A winter month was defined as being between November and February, inclusive	Positive
Rain	1 or 0	1 if the observed pedestrian was recorded as walking during rain, otherwise 0	Small Positive
Weekday	1 or 0	1 if the observed pedestrian was recorded as walking during a weekday, otherwise 0. Weekday was Monday to Friday, inclusive	Large Positive
Peak	1 or 0	1 if the observed pedestrian was recorded as walking during the times of commuter travelling, otherwise 0. The times of commuter travelling were defined as between 0800 to 0900 hours or 1700 to 1800 hours, based on the analysis of travel patterns shown in the Chapter Three	Large Positive

5.4.4 Data Collection Process

Based on the review of data collection techniques set out in Sections 4.2.1 to 4.2.6 in the previous Chapter, and the success of the data collected for the initial analysis, the method selected for gathering new data was video recording analysis. The procedure for abstracting data from the videotapes was the same as that described in Section 4.3.1 in the previous Chapter. A typical data collection rectangle or box consisted of the set up shown in Figure 5.1.

Figure 5.1: Layout of Data Collection Area Showing Typical Dimensions



In some of the sites selected the width varied depending on the dimensions of the walkway surveyed, but the data was standardised to match the HCM definitions by dividing the observed flow data by the width. This gave flow in units of pedestrians/minute/metre or the empirical equivalent which was used for comparison with the HCM methodology. Further details of the comparisons on the HCM methodology are shown in Chapter Six.

5.4.5 Comments on Variables and Data Collection Process

Whilst the selection of variables for potential use in improved models was based on those currently incorporated in the current HCM methodology and those over which a designer or planner may or may not have control, the results of the initial analysis (pilot study) reported in Chapter Four indicated that there potentially some weaknesses or limitations with the ranges of some of the variables.

The range of some of the variables was limited. For example, although it was possible to achieve a good range of flows there was little variation in the grades which enabled this to be achieved.

Although it is the authors view the data identified in this Chapter is very comprehensive and covers most travel conditions (including all LOS ranges), any findings from this study and also any new predictive models developed as a result of these findings would be based on known ranges and characteristics. In particular, some of the key variables might only produce suitable estimates within the ranges of the relevant data. This will be explored in Chapter Six, which will set out suitable ranges of the key variables of any new models developed.

Other potential limitations include observational weaknesses when collecting some of the data. While most of the data can be measured (e.g. flow, walkway width, etc) others are subjective. For example, age was obtained by visual inspection of the pedestrian. Clearly, different people might have varying opinions as to which banding to classify the same pedestrian.

Another point to note is that some of the variables in this set of data may produce positive variations under these survey conditions and data gathering techniques but negative results in another. This issue will be revisited in the conclusions in Chapter Eight after the results have been obtained and examined.

5.5 Data Collected

5.5.1 Use of the Existing Data

During this study, various organisations who are known to have been involved in pedestrian planning were approached to enquire if they had video tapes from pedestrian studies or surveys. These included those departments involved in transport planning within Local Authorities, Consultants and Public Transport Operators. Some of these organisations agreed to help, and provided videotapes from various surveys undertaken at different locations and walking environments throughout the country, during different times and seasons, and under different levels of pedestrian demand. Some data processed from these video tapes were also made available, but were not used because they were not compatible with the data required and described in Section 5.4.3 above.

5.5.2 Justification for Using the Videotapes

Use of the videotapes donated by the external organisations was considered highly sensible, since they contain a comprehensive set of information on walking speeds and the characteristics of the pedestrians for different conditions, environments, times, locations and constraints.

Some of these organisations are prominent in the field of pedestrian planning, and all the data that has been made available for this thesis has been audited or validated by independent third parties. These examinations included data and logic checks.

To reproduce similar video surveys would be very costly and wasteful of limited resources for this study. In addition to reducing survey costs, the videotapes of the surveys would also help to maximise the potential sources of data. This extra source of data would help provide the means by which phenomena can be explored in detail, without having to fit any data into artificial groups for the ease of collection or analysis. It was considered the best strategy for gathering information for this study was to use as much of the existing donated videotapes of past pedestrian surveys, complimented with the four video surveys undertaken for the initial analysis shown in Chapter Four.

However, the fact that there were a number of videotapes of past pedestrian surveys made available for this study does not mean they should be automatically used for this assessment. Not all this pedestrian information may be applicable, or within the last five years. Consequently, a review of the videotape surveys was undertaken before deciding upon which surveys to use. This is described below.

5.5.3 Review and Selection of Survey Sites

5.5.3.1 Basis for Selection of Sites

The first stage in the selection of sites from the previous surveys was to review the sites used in the original studies to find the most appropriate for this thesis. At the outset, the intention was to select sites that gave as much data on the potential variations of the variables identified in Section 5.4.3, based on what was considered to be the most important variables identified from the literature review.

The variables identified in Section 5.4.3 were prioritised in the following hierarchy based on their expected degree of influence on walking speed, the level of available data which the transport planner or designer can measure and also on the degree of control the pedestrian planner/designer can exert on them:

1. variables which are directly in the control of the transport planner or designer. These include all the variables used in the HCM (set out in Table 5.1) and the additional geometric variables identified from the literature review but are not used in the HCM methodology (shown in Table 5.2);

2. variables identified as being influential by the literature review which can not be controlled by the transport planner or designer but can be surveyed to a limited extent and possibly used. These include the variables representing the characteristics of the pedestrians (outlined in Table 5.3);

3. variables which can not be controlled by the pedestrian planner or designer. These include the variables representing the land-uses of the area, and the environment and time of travel (outlined in Tables 5.4 and 5.5).

Furthermore, the literature review showed most of the theory used to develop the HCM methodology was based on a narrow range of LOS's, design variables and characteristics of pedestrians.

Therefore, the sites and their associated videotape surveys were also selected based on their geometric variations between themselves, the potential for obtaining data about a wide range of LOS's (especially denser LOS ranges including D, E and F) and the potential for gathering data on different environmental conditions (both built and natural).

Of the various sites, five were selected for analysis of their video surveys, of which two were in Scotland and three were in England. The site from the initial analysis (pilot study) was added to maximise the potential sample size, which gave the following list of survey sites:

- Site A – Buchanan Street, Glasgow;
- Site B – Sauchiehall Street, Glasgow;
- Site C – Oxford Street, London;
- Site D – Temple Road, Newcastle;
- Site E – High Street, Basingstoke; and
- Site F – Princes Street, Edinburgh.

Details of each of these sites is set out in Appendix Two.

As mentioned above, to supplement the data available from the past studies the videotapes of the site in Princes Street in Edinburgh (East Scotland) used for the initial analysis were also added to the total stock of pedestrian surveys. This compliments the other surveys for the following reasons:

- the site and its associated videotape surveys had the required characteristics of geometry, land-uses and pedestrians. These also complimented the data from some of the other selected sites, thereby providing an opportunity to compare and contrast results. This would help validate the findings of the research; and

- the level of pedestrian demand experienced by the site included many different ranges, which also complimented the levels of demand at the other sites.

5.5.3.2 Summary of the Selected Sites and Surveys

A summary of the characteristics of the data obtained from the final selected sites is presented in Table 5.6. The existence of more than one set of survey videotapes at the same site was regarded as acceptable given the relatively wide range of pedestrian characteristics possible within each site and the differences between sites of other attributes (such as flow level, proportion of elderly pedestrians, walkway width and adjacent land-use).

Table 5.6: Characteristics of the Video Surveys Selected

Site	Type	Data	Numbers of Surveys	Source
Site A, Buchanan Street, Glasgow	Mixed Area	• LOS Ranges A to D • 5% Gradient • Thursday 1700 to 1800 hrs (2001) • Friday 0800 to 0900 hrs (2001) • Saturday 1400 to 1500 hrs (2001)	• 3 surveys in 2001 • total of 3 hours of data	Scott Wilson Consultants
Site B, Sauchiehall Street, Glasgow	Shopping Area	• LOS Ranges D to E • 0% Gradient • Friday 1700 to 1900 hrs (2001) • Thursday 1700 to 1900 hrs (2002) • Saturday 1400 to 1600 hrs (2002)	• 1 survey in 2001 • 2 surveys in 2002 • total of 6 hours of data	City of Glasgow Council
Site C, Oxford Street, London	Shopping Area	• LOS Ranges D to E • 0% Gradient • Friday 1700 to 1800 hrs (2000) • Thursday 1600 to 1900 hrs (1999) • Saturday 1400 to 1700 hrs (1999)	• 2 surveys in 1999 • 1 survey in 2000 • total of 7 hours of data	Westminster City Council
Site D, Temple Road, Newcastle	Residential Area	• LOS Ranges B/C to D • 2% Gradient • Friday 1700 to 1800 hrs (2002) • Thursday 1700 to 1800 hrs (2002)	• 2 surveys in 2002 • total of 2 hours of data	Scott Wilson Consultants
Site E High Street, Basingstoke	CBD Area	• LOS Ranges B to D • 0% Gradient • Thursday 1600 to 1900 hrs (2002) • Saturday 1400 to 1700 hrs (2002)	• 2 surveys in 2002 • total of 6 hours of data	Scott Wilson Consultants
Site F, Princes Street, Edinburgh	Shopping Area	• LOS Ranges C to F • 0% Gradient • Thursday 1600 to 1900 hrs (1999) • Saturday 1400 to 1700 hrs (1999) • Saturday 1400 to 1800 hrs (2001) • Monday 1400 to 1800 hrs (2001)	• 2 surveys in 1999 • 2 surveys in 2001 • total of 14 hours of data	By Author Using Edinburgh Council CCTV Monitoring System

As can be seen from Table 5.6, the combined surveys gave a total of 38 hours of data processed from videotapes covering a wide range of levels-of-services.

It was anticipated that the selected sites will help the analysis of the hypotheses developed and the variables identified based on the literature review as potentially influencing walking speed since they contain all the necessary data and cover different variations.

5.5.3.3 Advantages of this Data Gathering Process

This process of gathering data was chosen because it maximised the potential sample of data, reduced surveys costs and helped to create a flexible approach to the construction of suitable databases to store and analyse information. The last point is especially important, as there is a large body of methodological literature highlighting the significance of a flexible approach to data collection, so that new factors found to be relevant can be incorporated into the research project. For example, Washington et al (2003) believe that methods should be adopted to provide information required to undertake a comprehensive piece of research. They argue that new issues should be built in to the research rather than being eliminated for lying outside a pre-determined research structure.

5.6 Summary

Described in this chapter are the test hypotheses and the methodological approach that has been adopted to satisfy the six main research aims. In particular, a method to construct comprehensive databases to analyse issues has been produced, using as much existing data as appropriate gleaned from previous surveys and supplementing this data with new additional information from new surveys carried out during the initial analysis. Video surveys were chosen as the best technique for gathering new records. This has a major strength in being able to target individual sets of information, particularly when it is used to supplement existing statistics, as is the case in this study.

6 DEVELOPMENT OF WALKING SPEED RELATIONSHIPS

6.1 Introduction

The data assimilated from the various video surveys are used in this Chapter to undertake statistical tests to examine the suitability of current industry practice and identify a series of new statistical models which hopefully will have better predictive powers.

This Chapter begins with an overview of the data collected including details of the survey sites, information about the data gleaned and descriptions of the characteristics of the pedestrians surveyed. The new data is compared to the theories set out in the established research which was used to develop the methodology recommended in the Highway Capacity Manual (HCM). This is intended to check the new data collected. A series of statistical models were then prepared using the HCM methodology and tested to determine if they are applicable to the types of walking environments examined in this research. This showed that the HCM methodology did not predict walking speeds particularly well and it showed that a new form of model was required which encompasses more variables influencing walking speeds. To identify these additional variables, a statistical analysis was used to identify a number of factors found to significantly affect walking speeds. This analysis is described along with the resultant list of key variables identified for inclusion in a set of new statistical models. The best-fit models and the results of their initial validation are presented along with details of their operational ranges. A series of discussions on the findings is then presented. This includes a summary of the results and the categorisation of the variables required to use the new models. The levels of sensitivity of the variables in the new models are also discussed.

6.1.1 Modelling Strategy

The modelling strategy was based on enhancing the existing HCM methodology by adding additional variables identified in Chapter Five into the basic HCM relationship. Speed was used as the primary Measure of Effectiveness (MOE) as the current HCM uses speed. In particular, the HCM's arterial analysis chapter (Chapter 11; TRB, 2000) uses overall average travel speed as the MOE. In addition, the review of industry practices in the UK and other parts of Europe by Zegeer et al (1994) has shown that speed is predominantly used as a MOE, and also as a means of testing the effectiveness of enhancements to existing walking facilities or comparing different designs of new infrastructure. Furthermore, the literature review showed that speed is one of the main parameters used by pedestrian modelling software programs like PEDROUTE, LEGION and other leading industry models (see Section 2.3.2 of Chapter Two).

The model development process followed a model assessment criteria used to guide the development of the new models. This is explained in Section 6.5.2. Since there were a large number of potential explanatory variables, a structured approach to model development was therefore required. This comprised a five-stage development of final models, set out in Section 6.5.3. The resultant model development process can be summarised as follows:

- use speed as the primary MOE and reproduce the basic HCM relationship using the variables in Table 5.1 of Chapter Five, with speed as the independent variable;

- expand the basic HCM relationship by adding in the other variables identified in Chapter Five, using the structured approach of best subset modelling to model development (see Section 6.5.3). The best subset approach to modelling is described by Krzanowaski (1998); and

- test the impacts of the variables on the model as each category of variable is added using the model assessment criteria, as in Section 6.5.2 (in accordance with the best subset approach).

The intention from the outset was to test all the variables identified in Chapter Five, and examine their significance. The decision to keep the variable in the model was based solely on its performance in the model assessment criteria.

Combined with the selection process of the variables used in the analysis, as explained in Chapter Five, the author believes the above modelling strategy would lead to improved models with a logical set of variables.

6.2 Overview of the New Data Collected

6.2.1 About the Survey Sites

The recorded videotapes from the various studies of pedestrian movements were processed and data abstracted using the steps explained in the Research Method described in Chapter Five, the case for which was reviewed and argued in the initial analysis shown in Chapter Four. A total of 17 surveys were processed producing 17 sets of data as shown in Table 6.1.

Table 6.1: Labelling of the Data Sets

Data Set	Site	Time/Date of Survey
1	Site A, Buchanan Street, Glasgow	Thursday 1700 to 1800 hours (2001)
2	Site A, Buchanan Street, Glasgow	Friday 0800 to 0900 hours (2001)
3	Site A, Buchanan Street, Glasgow	Saturday 1400 to 1500 hours (2001)
4	Site B, Sauchiehall Street, Glasgow	Friday 1700 to 1900 hours (2001)
5	Site B, Sauchiehall Street, Glasgow	Thursday 1700 to 1900 hours (2002)
6	Site B, Sauchiehall Street, Glasgow	Saturday 1400 to 1600 hours (2002)
7	Site C, Oxford Street, London	Friday 1700 to 1800 hours (2000)
8	Site C, Oxford Street, London	Thursday 1600 to 1900 hours (1999)
9	Site C, Oxford Street, London	Saturday 1400 to 1700 hours (1999)
10	Site D, Temple Road, Newcastle	Friday 1700 to 1800 hours (2002)
11	Site D, Temple Road, Newcastle	Thursday 1700 to 1800 hours (2002)
12	Site E, High Street, Basingstoke	Thursday 1600 to 1900 hours (2002)
13	Site E, High Street, Basingstoke	Saturday 1400 to 1700 hours (2002)
14	Site F, Princes Street, Edinburgh	Thursday 1600 to 1900 hours (1999)
15	Site F, Princes Street, Edinburgh	Saturday 1400 to 1700 hours (1999)
16	Site F, Princes Street, Edinburgh	Saturday 1400 to 1800 hours (2001)
17	Site F, Princes Street, Edinburgh	Monday 1400 to 1800 hours (2001)

6.2.2 Characteristics of Speed, Flow and Pedestrian Space

A statistical overview derived from using SPSS is summarised in the following sections. The main characteristics of the data collected are set out in Appendix Three.

A summary of the statistical review is presented in Table 6.2. This shows the sample of observations obtained from each data set along with the average walking speed, the average two-way pedestrian flow, the average pedestrian space (the reciprocal of pedestrian density) at the middle of the observation area and the corresponding Level-of-Service (LOS) range as defined in the 2000 edition of the HCM (TRB, 2000). Flow was used in defining the LOS indicator (see Table 2.2 in Chapter Two) as this is commonly used in pedestrian studies; there may be small differences in the resultant LOS values if average speed or average space is used.

Table 6.2 was prepared to allow a comparison with the same values set out in the various tables in the HCM (TRB, 2000).

Examination of Table 6.2 shows that the data collected from the 17 surveys cover values on walking speeds, two-way flows and pedestrian space that are applicable to all LOS ranges. When all data sets are combined the data yields an average LOS range of D but this is mainly due to the large numbers of observations in data sets 14 and 15, which have a much larger sample size than any of the others.

Table 6.2: Summary Characteristics of the Data Collected

Data Set	Survey Site	N	Average Speed (m/s)	Average Two-Way Flow (ped/min/m)	Average Space (m^2/ped)	LOS
1	Site A	113	0.929 (0.277)	31.054 (11.631)	4.135 (1.494)	C
2	Site A	137	0.927 (0.267)	37.459 (14.536)	3.793 (1.619)	D
3	Site A	97	0.934 (0.252)	22.285 (6.533)	4.661 (1.346)	A
4	Site B	391	1.117 (0.246)	34.961 (10.592)	2.660 (0.409)	D
5	Site B	476	1.102 (0.229)	34.193 (9.706)	2.679 (0.394)	D
6	Site B	569	0.733 (0.082)	49.556 (9.812)	1.126 (0.108)	E
7	Site C	317	0.618 (0.058)	41.158 (7.371)	0.686 (0.094)	D
8	Site C	779	0.624 (0.059)	41.436 (7.445)	0.689 (0.096)	D
9	Site C	902	0.583 (0.057)	49.129 (9.828)	0.530 (0.021)	E
10	Site D	93	1.146 (0.347)	32.189 (13.274)	4.833 (1.767)	C
11	Site D	99	0.886 (0.249)	33.759 (11.911)	3.412 (1.380)	D
12	Site E	652	1.202 (0.268)	23.110 (7.769)	4.312 (0.720)	B
13	Site E	791	0.792 (0.089)	24.976 (4.498)	3.041 (0.350)	C
14	Site F*	713	1.119 (0.241)	34.534 (9.905)	2.683 (0.408)	D
15	Site F*	852	0.742 (0.083)	50.453 (10.168)	1.126 (0.112)	E
16	Site F*	257	0.666 (0.064)	60.206 (10.250)	0.493 (0.067)	E
17	Site F*	297	0.627 (0.063)	76.349 (14.535)	0.384 (0.015)	F
All Data	All Sites	7,535	0.836 (0.275)	40.473 (15.231)	1.957 (1.452)	D

Notes: Figures in Brackets are Standard Deviation
* denotes sites surveyed by the author

The definition of LOS was based on flow and there could be small differences in the classification if speed or pedestrian space was used.

6.2.3 Details of the Pedestrian Characteristics

Tables 6.3a and 6.3b show a comparison of the pedestrian types from the data.

Table 6.3a: Comparison of the Pedestrian Types (Data Sets 1 to 10)

Ped Type	Data Sets									
	1	2	3	4	5	6	7	8	9	10
Male	46.9%	52.5%	43.3%	43.7%	42.9%	41.7%	57.4%	58.9%	42.6%	51.6%
Female	53.1%	47.5%	56.7%	56.3%	57.1%	58.3%	42.6%	41.1%	57.4%	48.4%
Child	5.3%	10.9%	3.2%	11.0%	8.2%	9.9%	6.9%	11.0%	9.6%	6.5%
Young Adult	46.5%	43.2%	41.2%	30.4%	33.0%	30.2%	31.5%	31.7%	33.7%	45.2%
Middle Adult	9.7%	3.6%	30.9%	20.5%	22.7%	25.5%	25.6%	22.8%	21.9%	10.7%
Elderly	38.5%	42.3%	24.7%	38.1%	36.1%	34.4%	36.0%	34.5%	34.8%	37.6%
Infirm	4.4%	1.5%	2.1%	1.8%	1.5%	8.8%	0.9%	0.5%	0.9%	1.1%
Group	9.7%	8.8%	6.1%	10.2%	14.9%	3.9%	1.9%	2.7%	4.0%	4.3%

Table 6.3b: Comparison of the Pedestrian Types (Data Sets 11 to 17, and All Data Sets Combined)

Ped Type	Data Sets							
	11	12	13	14	15	16	17	All
Male	56.7%	44.9%	50.7%	38.6%	38.8%	37.7%	39.4%	46.36%
Female	43.3%	55.1%	49.3%	61.4%	61.2%	62.3%	60.6%	53.64%
Child	11.3%	7.5%	6.6%	9.7%	10.6%	10.5%	10.8%	8.81%
Young Adult	37.1%	35.4%	34.1%	30.4%	34.9%	31.5%	28.6%	35.19%
Middle Adult	3.1%	22.9%	22.5%	25.5%	19.6%	24.9%	22.2%	19.69%
Elderly	48.5%	34.2%	36.8%	34.4%	34.9%	33.1%	38.4%	36.31%
Infirm	2.1%	1.1%	1.5%	1.0%	1.6%	0.4%	0.7%	1.88%
Group	7.2%	14.2%	4.9%	5.2%	3.3%	4.3%	3.0%	6.39%

The proportion of male subjects varies from 37.7% to 58.9% and the percentage of female ranges from 41.3% to 62.3%. The proportion of children varies from 3.1% to 11.3%; quite a large variation compared to some of the other age groups. The percentage of young adults is between 28.6% and 46.9% and the proportion of middle adults ranges from 3.1% to 30.9%, both of which are much wider than some of the others. The percentage of elderly is from 24.7% to 48.5%, again a very wide range. The proportion of infirm pedestrians ranged from 0.4% to 8.8%. The percentage of pedestrians in groups of 2 or more ranged from 1.9% to 14.2%, also wide.

6.3 Comparisons of the New Data with the Established Theories

6.3.1 Objectives of this Analysis

The results of the pilot study raised a number of questions about the level of accuracy of the estimates obtained using the HCM methodology. It was shown that the HCM methodology was describing only 59% of the variations suggesting that there are more factors that influence pedestrian walking speed other than just pedestrian flow and space as recommended by the HCM (TRB, 2000). It was also shown in the literature review that there are some weaknesses in the HCM methodology, including biases towards low ranges of LOS (see Section 2.5 of Chapter Two). These findings raised a question about the applicability of the HCM methodology in pedestrian studies of the types of walking environments in the UK that are the subject of this thesis. It may be that the HCM methodology is not suitable in its current form to adequately estimate walking speeds for these types of walking areas. This section therefore seeks to explore these issues.

This section begins by comparing the characteristics of the new data with those of the currently used empirical relationships. This is intended to validate the new data and confirm it is showing similar walking characteristics to what the previously established relationships advise are to be expected from pedestrians. Confirming the new data is replicating the currently used empirical relationships will also provide confidence that the new data has been processed in line with the latest industry-standards.

This section will then describe a statistical model that was developed based on the recommended HCM methodology and using all of the new data collected aggregated together into one large database of walking movements. Statistical indicators will be presented to gauge the level of predictive power of the HCM methodology.

6.3.2 Comparisons of the Previously Established Relationships with the New Data

This section compares the characteristics of the new data collected with the previously established relationships from past research that was used to underpin the methodology recommended in the HCM. This is undertaken using graphical representations of the following key relationships:

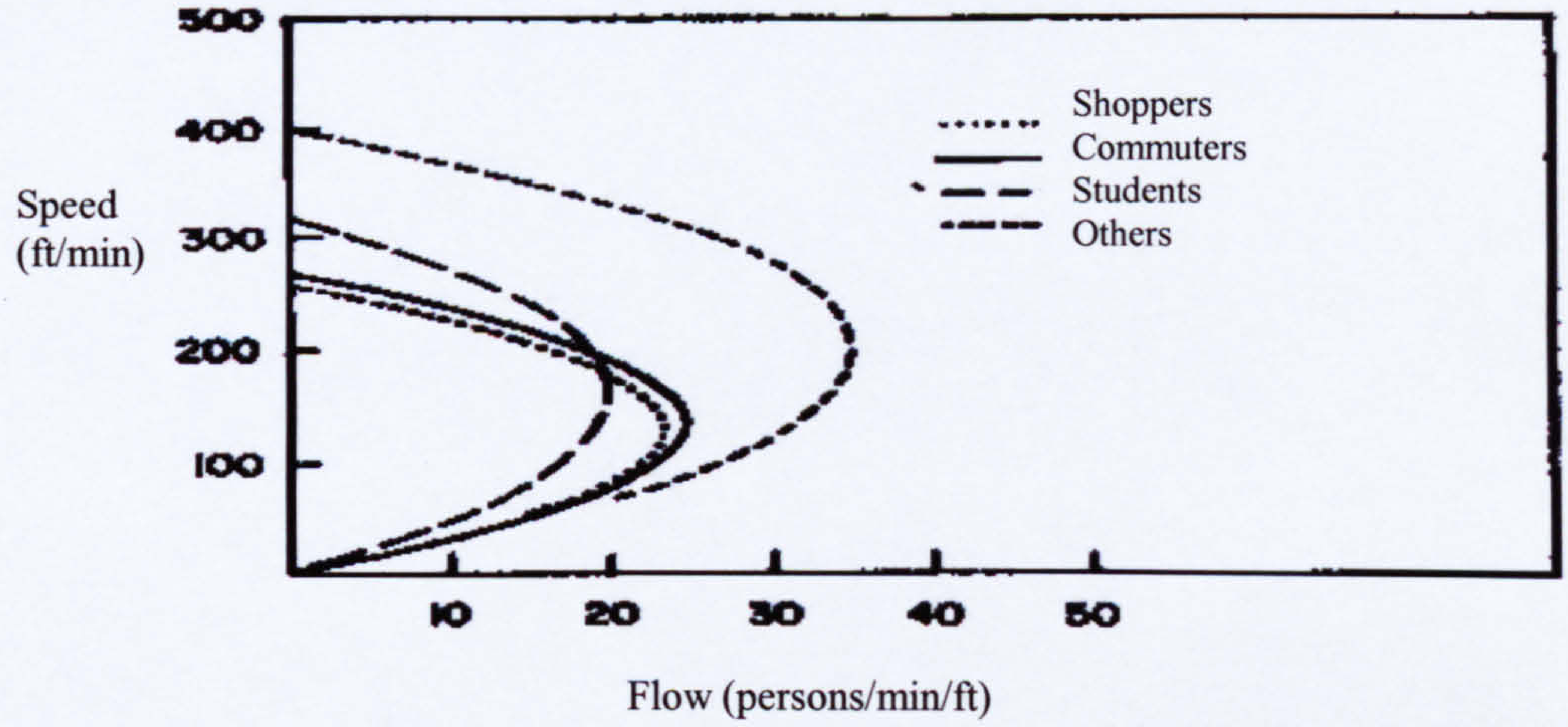
- speed versus flow;
- speed versus density;
- speed versus pedestrian space (the reciprocal of density); and
- flow versus pedestrian space.

The graphs used from the previously established relationships have units of speed, flow, space and density based on feet (ft.) or square-feet (ft^2). The new data collected for use in this study is in metres (m) and therefore appropriate factors were applied to the observations of walking speed, flow, density and pedestrian space to convert them to empirical units so they could be compared with the previously established relationships.

6.3.2.1 Speed versus Flow

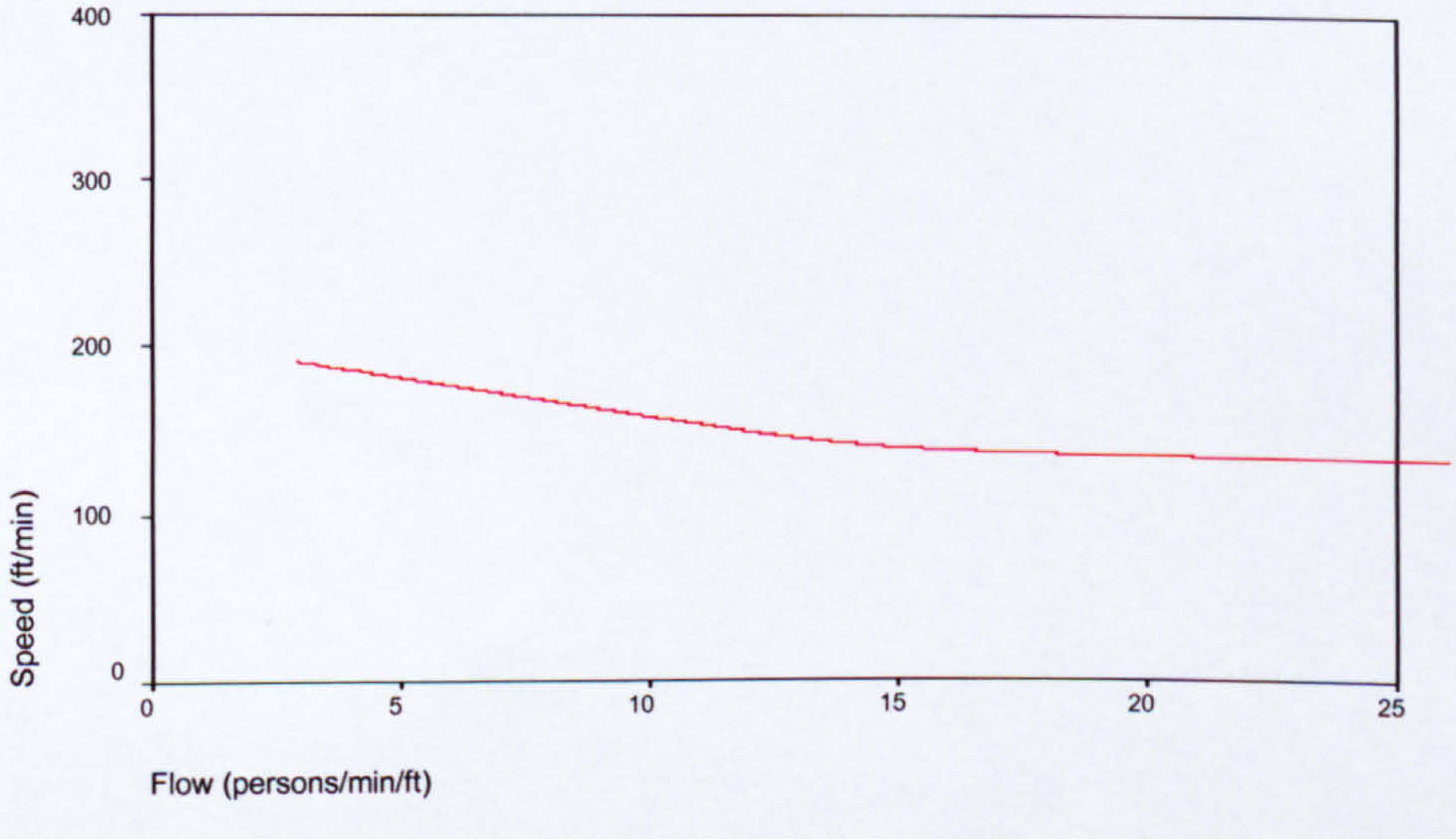
Figure 6.1a shows the graphical relationship of speed versus flow from Pushkarev and Zupan (1975a and 1975b). This shows that as pedestrian flow increases walking speed declines until breakdown occurs after which both flow and speed reduce together. Figure 6.1b shows the same graphical relationship of speed versus flow using the new data obtained from the surveyed sites in this research; this is a smooth spline through the data to represent the overall tendency.

Figure 6.1a: Previously Established Relationship of Speed versus Flow



Source: Pushkarev and Zupan (1975a and 1975b)

Figure 6.1b: New Data graphical relationship of Speed versus Flow



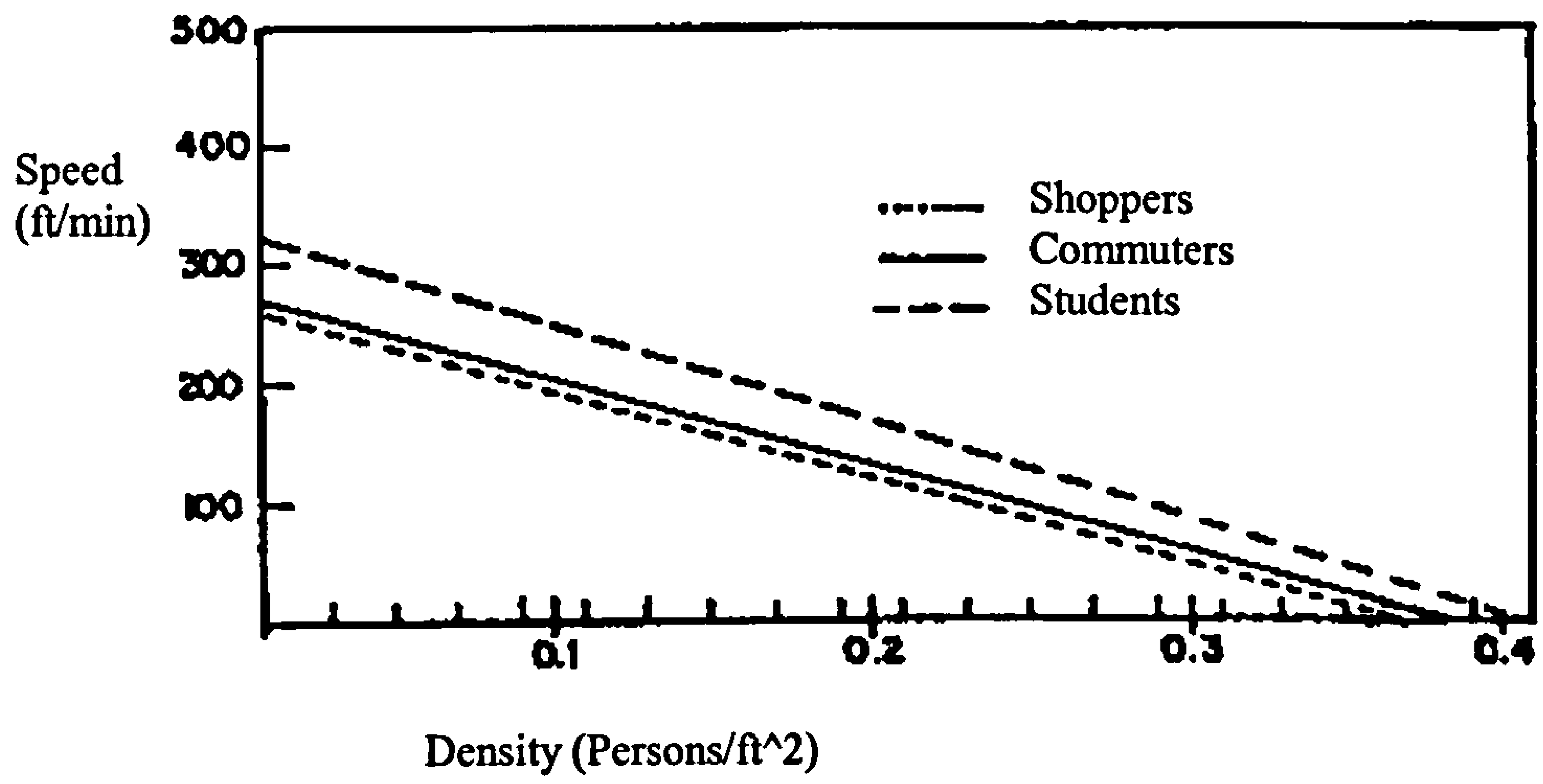
Note the scale of the observed flows from the new data ranged from about 2.5 persons/min/ft to just over 25 persons/min/ft. In addition the scale of the observed walking speeds from the new data ranged from about 120 ft/min to 200 ft/min. This means that it is only possible to compare the two relationships over these ranges.

Comparing the two graphs over these ranges shows the relationship of the data obtained from the new surveys seems to follow the Pushkarev and Zupan relationship. The scale is different but the shape of the graph suggests the data is compatible with the theories that were used to underpin the HCM methodology.

6.3.2.2 Speed versus Density

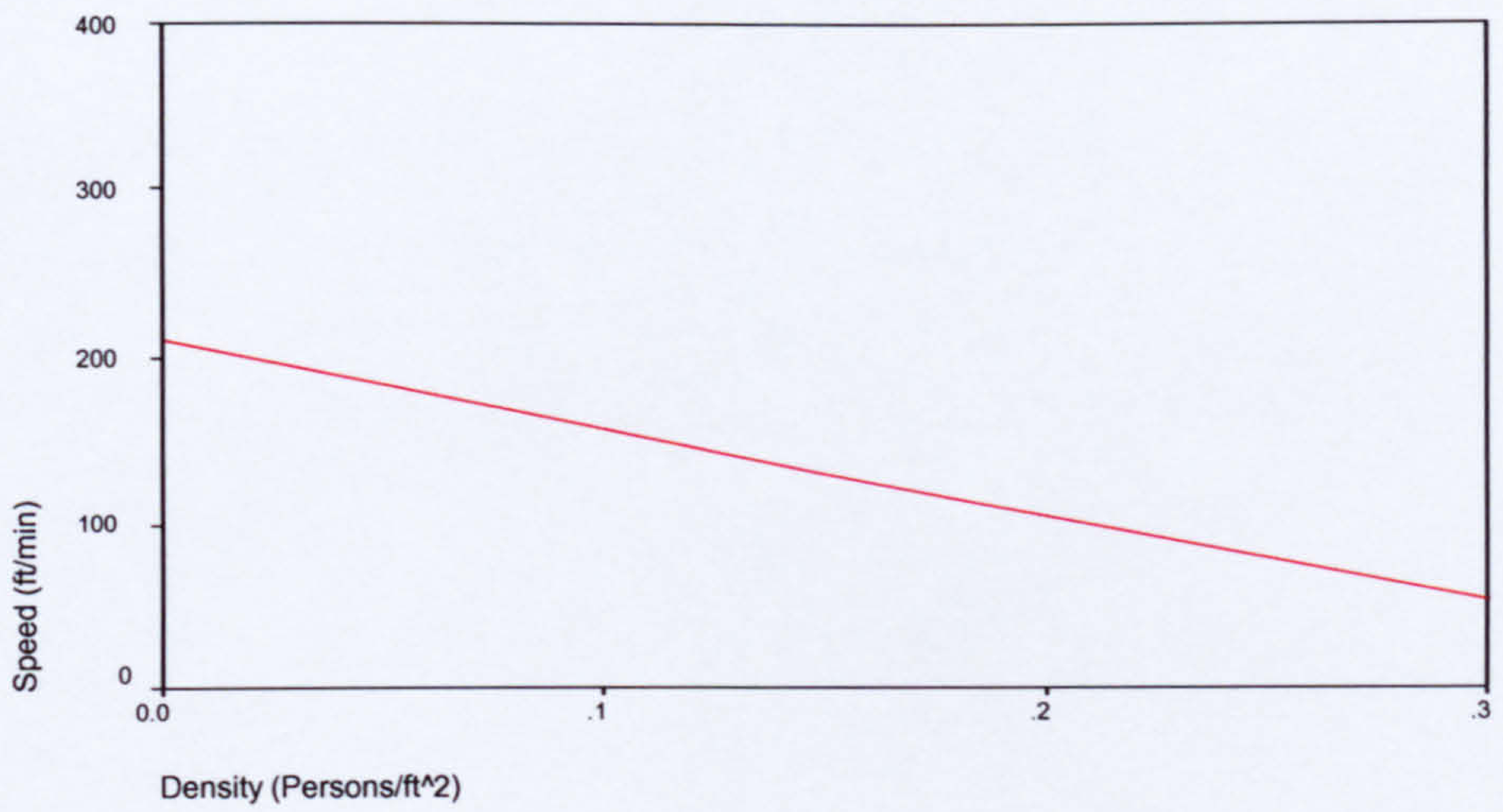
Figure 6.2a shows the graphical relationship of speed versus density as set out in Pushkarev and Zupan (1975a and 1975b). Similarly, Figure 6.2b shows the graphical relationship of speed versus density obtained using the new data. This is also a smooth spline through the data to represent the overall tendency.

Figure 6.2a: Established Theory of Speed versus Density



Source: Pushkarev and Zupan (1975a and 1975b)

Figure 6.2b: New Data graphical relationship of Speed versus Density

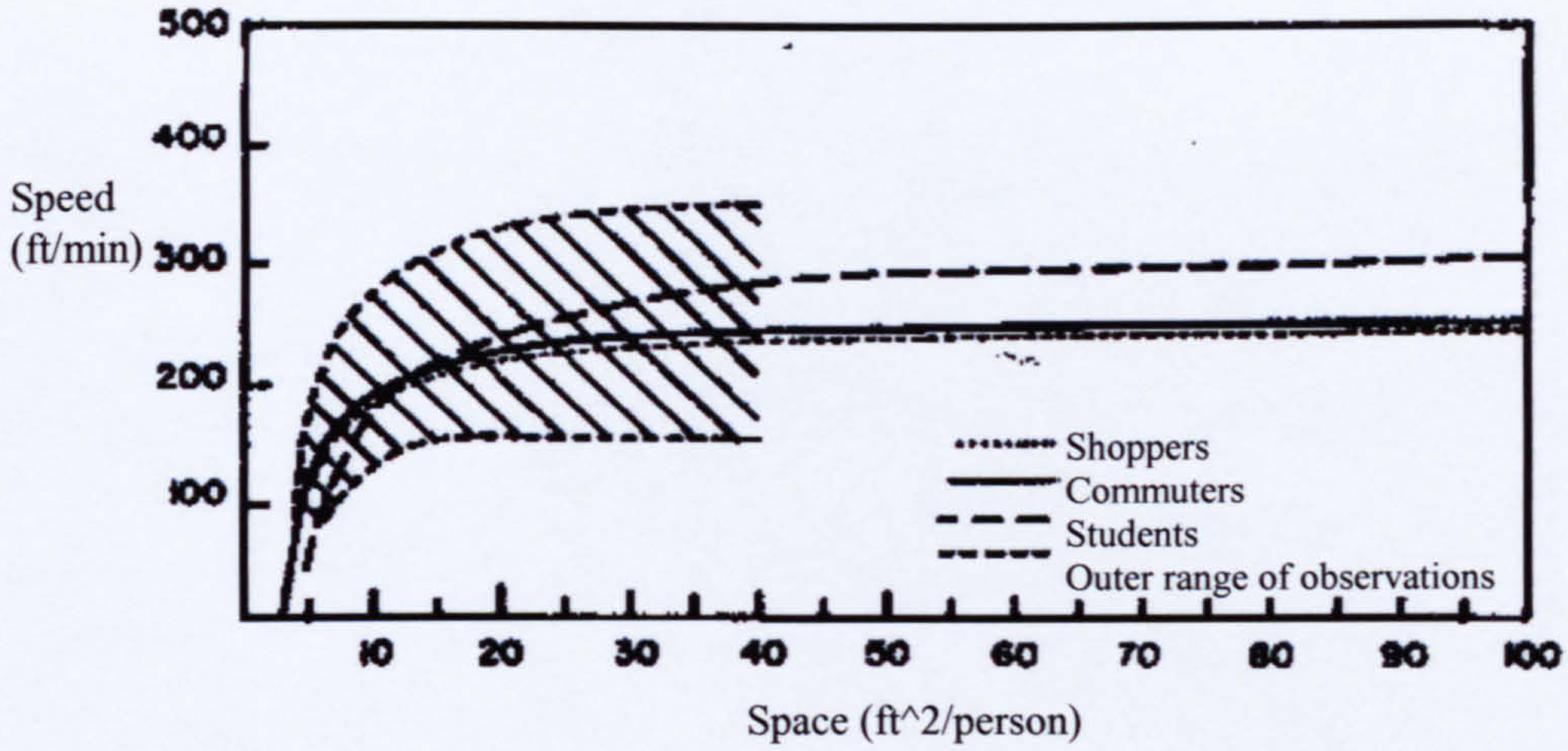


The Pushkarev and Zupan graph shows that as pedestrian density increases and pedestrian space decreases there is a reduction in the average speed of the pedestrian stream. The graph produced using the new data follows this relationship, indicating the data is compatible.

6.3.2.3 Speed versus Pedestrian Space

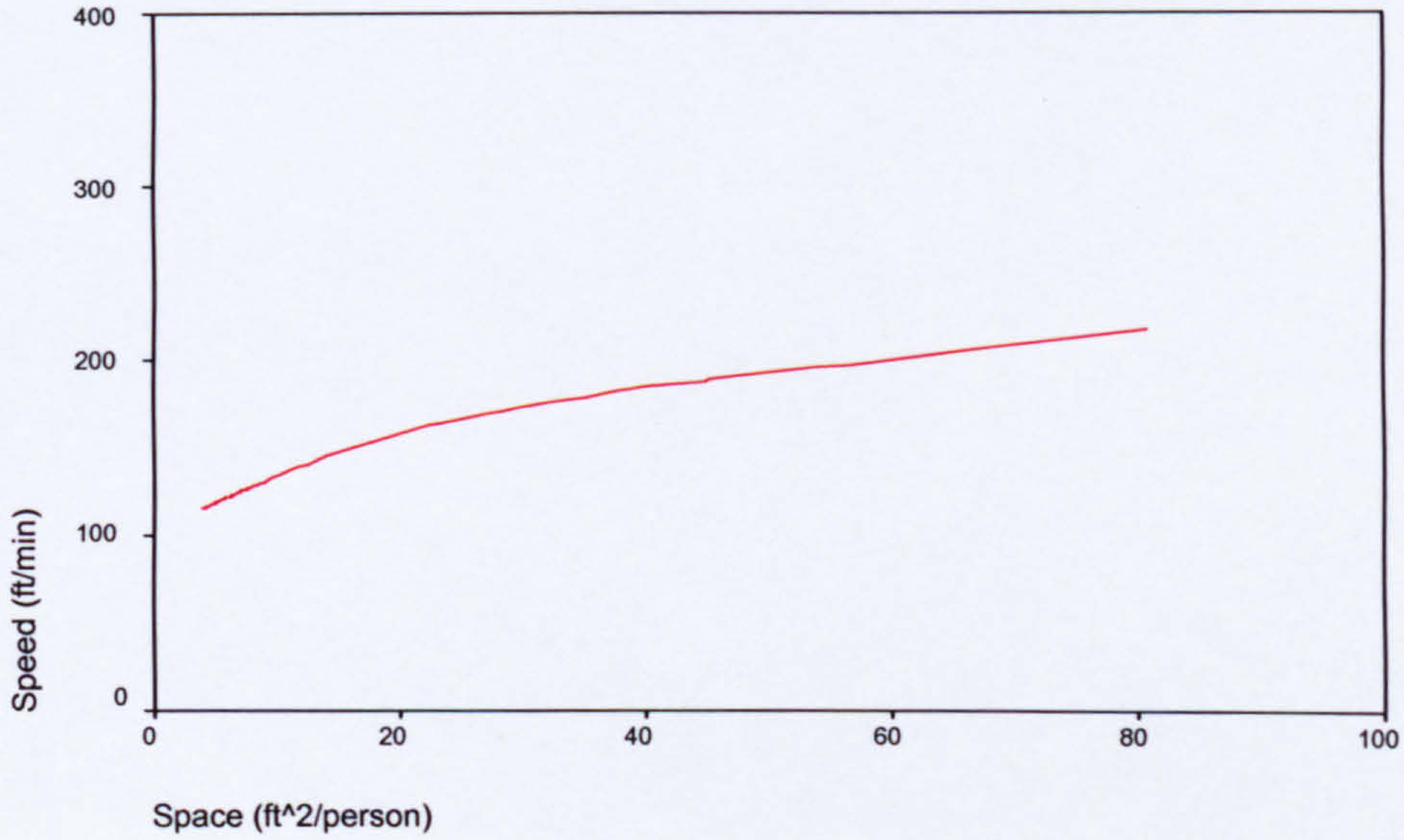
Figure 6.3a shows the Pushkarev and Zupan (1975a and 1975b) graphical relationship of speed versus pedestrian space (the reciprocal of density). The corresponding graphical relationship of speed versus pedestrian space from the new data is shown in Figure 6.3b, derived from a smooth spline to show the general tendency.

Figure 6.3a: Established Theory of Speed versus Pedestrian Space



Source: Pushkarev and Zupan (1975a and 1975b)

Figure 6.3b: New Data graphical relationship of Speed versus Pedestrian Space

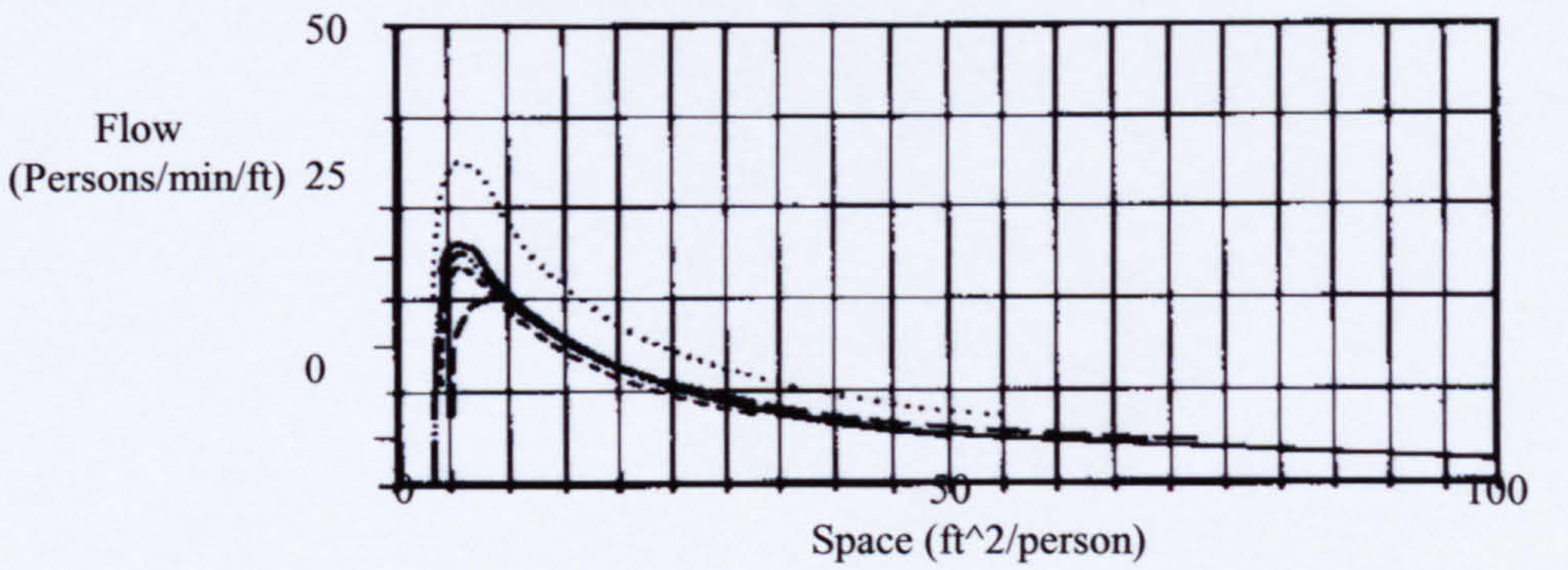


The Pushkarev and Zupan graph shows that as pedestrian space increases it becomes less influential in affecting the average speed of the pedestrian stream. This suggests that during high areas of pedestrian space walking speed is affected by other factors. The graph produced using the new data follows this relationship.

6.3.2.4 Flow versus Pedestrian Space

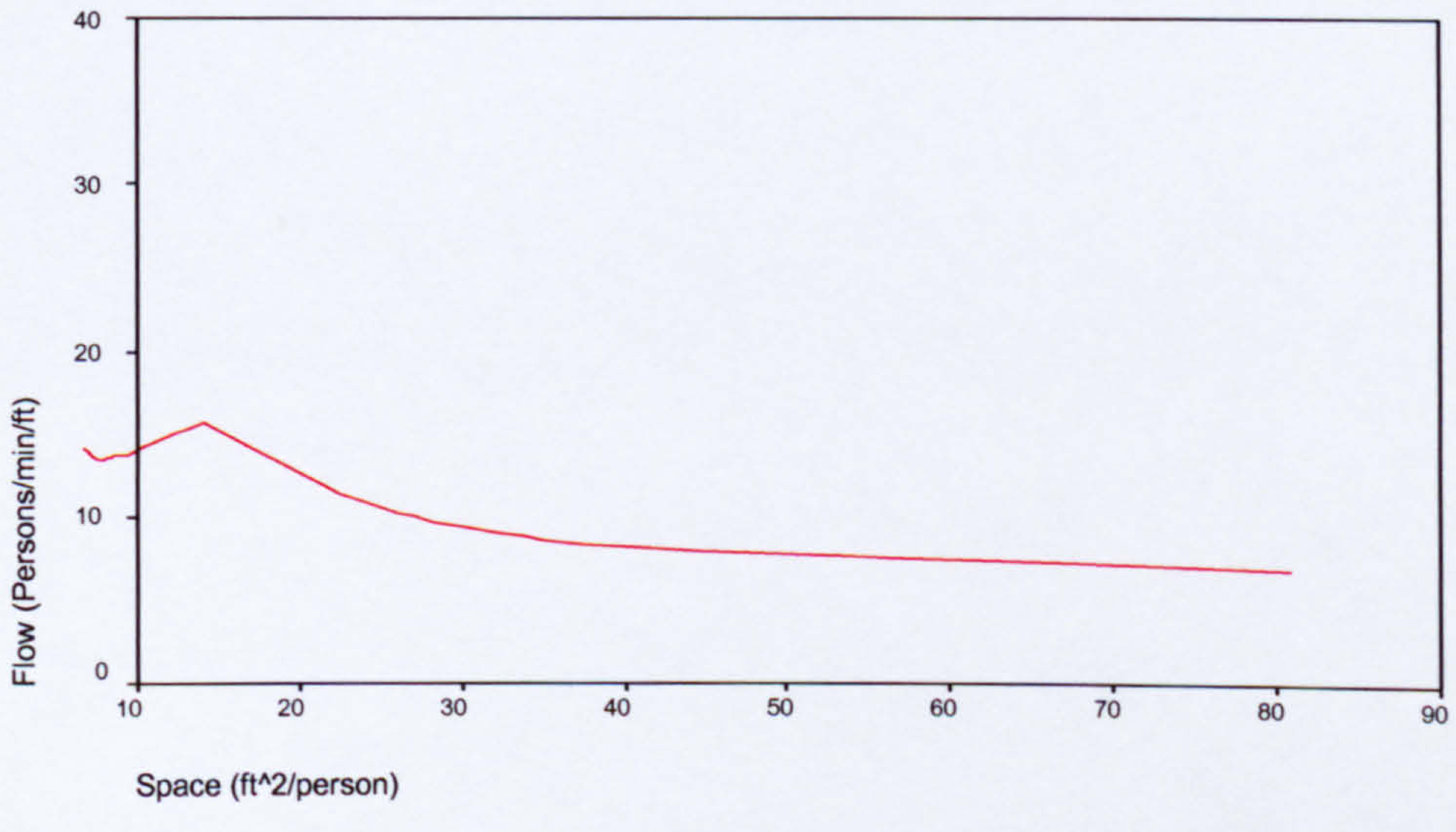
Shown in Figure 6.4a is the graphical relationship of flow versus pedestrian space from Fruin (1971) and shown in Figure 6.4b is the corresponding graphical relationship (smooth spline curve) of flow versus pedestrian space from the new data.

Figure 6.4a: HCM graphical relationship of Flow versus Pedestrian Space



Source: Fruin (1971)

Figure 6.4b: New Data graphical relationship of Flow versus Pedestrian Space



It may be seen from the Fruin graph that the maximum flow falls within a very narrow range of space. As space is reduced below 5 ft^2/ped the flow rate declines. The graph produced using the new data follows this relationship, indicating the data is compatible.

6.3.2.5 Findings from the Graphical Comparisons

The graphical comparisons of the new data against the figures established in the HCM broadly shows that the data collected is in line with the HCM. This provides confidence that the new data has been processed in line with industry-standards and shows similar walking characteristics as expected.

The question now is whether the HCM methodology is applicable to the types of walking environments that are the subject of this research (on-street walkways in UK shopping and Central Business District areas). This is pursued in the following section.

6.3.3 Comparisons using the HCM Methodology

6.3.3.1 Speed versus Flow and Density

A statistical relationship was developed based on the recommended HCM methodology. The HCM methodology estimates flow using speed and pedestrian space – the reciprocal of density – as follows (TRB, 2000):

$$V = S / M$$

where: V = flow or volume;

S = speed; and

M = pedestrian space = 1/density.

This relationship can be re-arranged as follows:

$$V = S \times D$$

$$\Rightarrow \quad S = V / D$$

$$\Rightarrow \quad \text{Ln}\, S = \text{Ln}\, V - \text{Ln}\, D$$

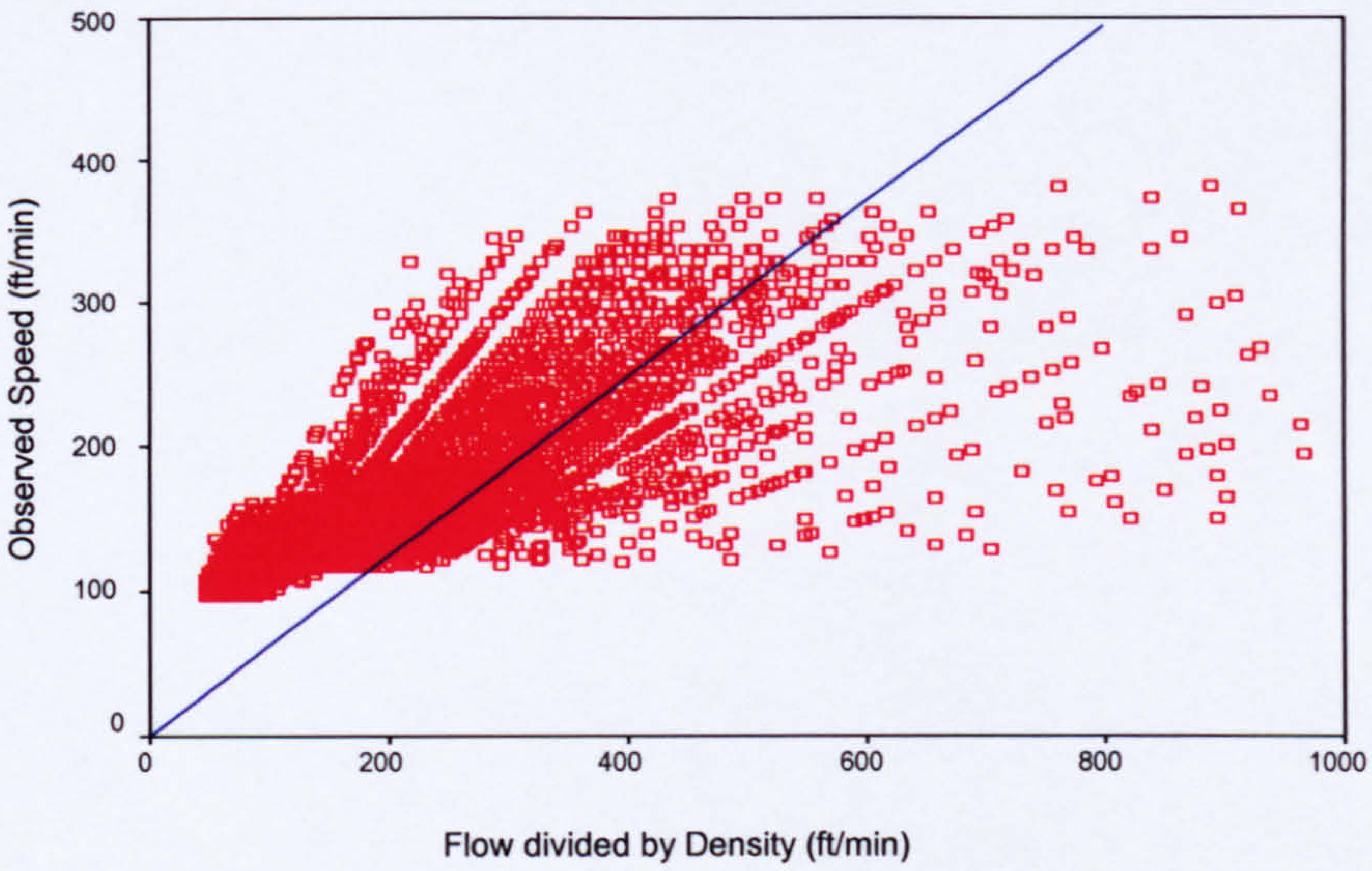
where: D = density; and

Ln = the natural logarithm.

6.3.3.2 Relationship between HCM methodology and Observed Data

To identify the relationship between the HCM methodology and the observed data a graphical plot of the flow divided by the density (namely V / D in the methodology described in Section 6.3.3.1 above) versus the observed walking speeds was produced. This is shown in Figure 6.5.

Figure 6.5: Observed versus HCM Data



The best-fitting line from the data closely follows a 45-degree slope as expected.

6.3.3.3 Best-fit HCM Relationship

The statistical relationship developed using the HCM methodology used all of the data collected from the 17 surveys, aggregated into one large database. However, to allow for some validation of the resultant relationship from the HCM methodology only 80% of the aggregated data was used to develop the relationship and 20% was used as a hold-out sample for testing the relationship. The resultant relationship developed using the HCM methodology is shown in Table 6.4.

Table 6.4: Best-fit HCM Relationship developed from New Data

Coefficients[a,b]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	LNDEN	-.448	.004	-1.075	-115.863	.000
	LNFLOW	.674	.006	1.111	119.842	.000

a. Dependent Variable: LN_SPEED

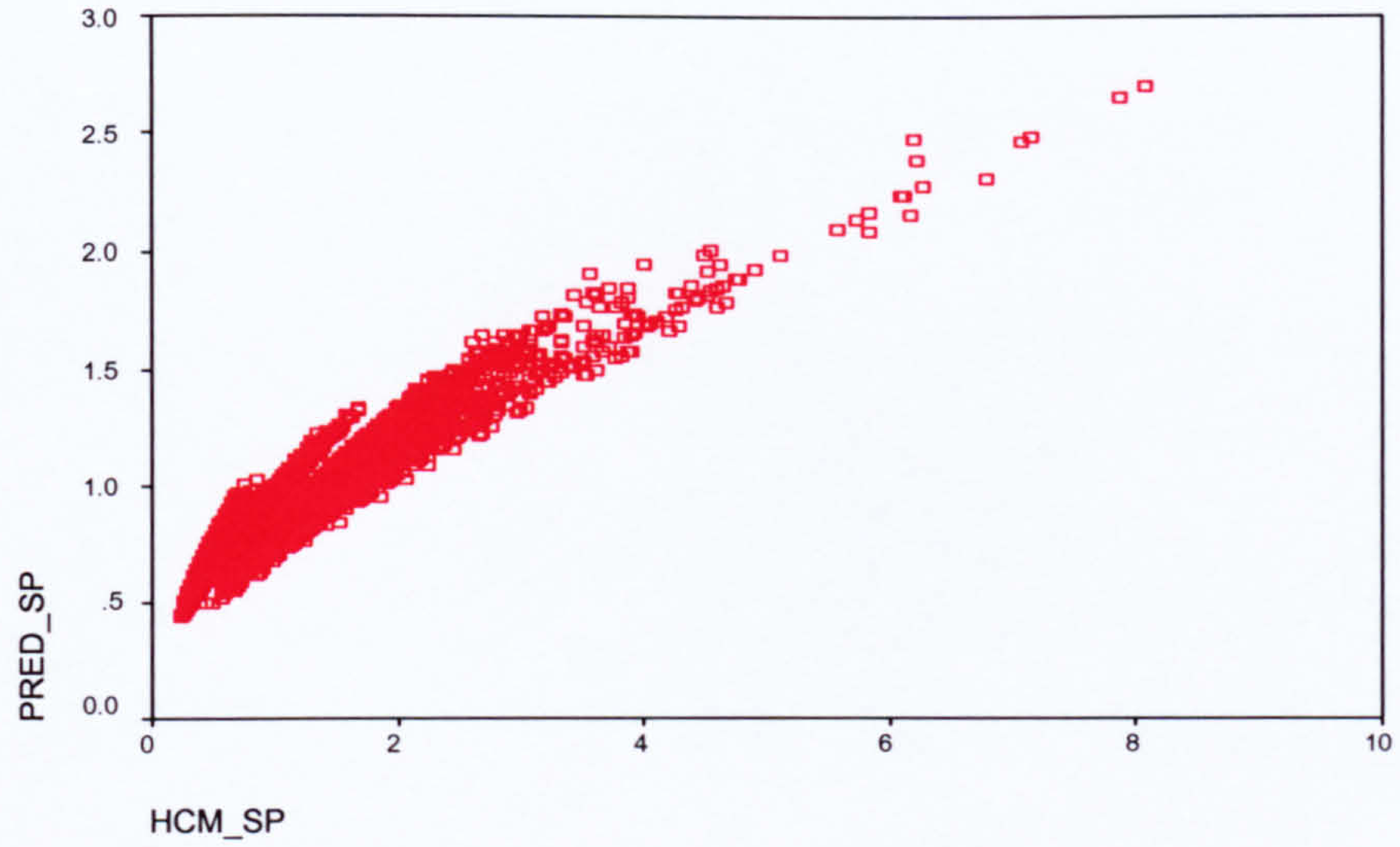
b. Linear Regression through the Origin

Both variables used (total two-way flow and density) were found to be statistically significant at the 95% Confidence Level, and the parameter LNDEN (the natural logarithm of density) is right-signed suggesting the relationship is as one would expect. However, the HCM methodology only provided an adjusted R-square value of 65%. This is not much better than the results of the pilot study (the best fitting relationship only provided 59%).

6.3.3.4 Testing the HCM Statistical Relationship

Estimates using the best-fit statistical relationship based on the HCM methodology (Table 6.4) were undertaken using the 20% hold out sample. Figure 6.6 shows a graphical diagram the observed and the predicted speeds using the new relationship.

Figure 6.6: Comparison of Observed and Predicted Speeds using the HCM Relationship



A series of statistical tests on the goodness-of-fit of the estimates gave a Pearson correlation coefficient between the predicted and observed of 0.425 and the mean absolute percentage error (MAPE) is 23.6%.

6.3.4 Concluding Remarks

These tests suggest the HCM methodology only describes less than two-thirds of the variations that influence walking speeds indicating there are more factors which influence pedestrian speeds (not just flow and space). This finding is almost identical to that found from the initial pilot study undertaken on a walkway in a shopping area in Edinburgh and has confirmed the initial conclusion from the pilot study. Expanding the available cases has not improved the level of predictive power gained from the HCM methodology nor did it disprove the hypothesis that more variables should be used to improve the estimation of walking speed. Therefore, it was concluded that a new form of statistical model is required which encompasses more variables than are currently used by the HCM methodology. The identification of these additional variables is set out below in the following section.

6.4 Statistical Tests to Identify Variables which affect Walking Speeds

6.4.1 Gender of the Pedestrian

A t-test was undertaken to ascertain whether gender affects walking speed. The analysis of the Data Sets is presented in Table 6.5 below.

Table 6.5: Results of T-Tests on Gender

Data Set	Females			Males			Significant at the 5% level
	Obs.	Mean	Standard Error Mean	Obs.	Mean	Standard Error Mean	
1	53	0.063	0.004	60	0.158	0.033	No
2	65	0.132	0.033	72	0.095	0.030	No
3	42	0.095	0.042	55	0.104	0.031	No
4	220	0.093	0.014	171	0.080	0.017	No
5	272	0.071	0.012	204	0.085	0.015	No
6	332	0.313	0.006	237	0.320	0.007	No
7	135	0.484	0.008	182	0.488	0.007	No
8	322	0.472	0.005	457	0.480	0.005	No
9	520	0.548	0.004	382	0.540	0.005	No
10	45	0.149	0.044	48	0.042	0.040	No
11	42	0.172	0.037	57	0.141	0.034	No
12	359	0.179	0.011	293	0.138	0.012	Yes
13	401	0.242	0.005	390	0.237	0.006	Yes
14	438	0.089	0.0098	275	0.093	0.013	No
15	521	0.307	0.005	331	0.301	0.006	No
16	160	0.406	0.007	97	0.417	0.010	No
17	180	0.478	0.007	117	0.464	0.010	No
All	4109	0.218	0.006	3426	0.246	0.006	No

As can be seen, gender was only significant in two of the data sets.

Overall, the above analysis suggests that gender does not have a significant effect on walking speeds, indicating incorporating gender would not improve modelling in these types walking environments and conditions.

6.4.2 Infirm versus Able-Bodied Pedestrians

A t-test was undertaken to identify whether being infirmed affects walking speed.

Unfortunately, the sample sizes obtained from the 17 surveys were considered to be too low to allow analysis of the data sets separately, but when they were combined they gave a total of 89 observed infirmed pedestrians.

Therefore, analysis was carried out using the data from all the data sets combined together as presented in Table 6.6.

Table 6.6: Results of T-Tests on being Infirm or Able Bodied

Data Set	Infirm			Able-bodied			Significant at the 5% level
	Obs.	Mean	Standard Error Mean	Obs.	Mean	Standard Error Mean	
All	89	-0.363	0.025	7446	-0.230	0.004	Yes

The above analysis suggests being an infirm pedestrian does significantly reduce walking speeds, as one would expect.

6.4.3 Pedestrians Walking in Groups

A t-test was undertaken to examine whether walking in groups of 2 or more effects pedestrian speed. The analysis of the data is presented in Table 6.7 below.

Table 6.7: Results of T-Tests on Pedestrians Walking in Groups

Data Set	Part of a Group			Walking Alone			Significant at the 5% level
	Obs.	Mean	Standard Error Mean	Obs.	Mean	Standard Error Mean	
1	11	-0.372	0.027	102	-0.086	0.027	Yes
2	12	-0.407	0.017	125	-0.084	0.023	Yes
3	6	-0.437	0.022	91	-0.078	0.025	Yes
4	40	-0.040	0.021	351	0.102	0.012	Yes
5	71	-0.008	0.017	405	0.092	0.010	Yes
6	22	-0.413	0.013	547	-0.312	0.005	Yes
7	6	-0.595	0.013	311	-0.484	0.005	Yes
8	21	-0.609	0.008	758	-0.473	0.003	Yes
9	36	-0.650	0.010	866	-0.540	0.003	Yes
10	4	0.160	0.061	89	0.105	0.031	Yes
11	7	-0.374	0.039	92	-0.137	0.026	Yes
12	93	0.049	0.014	559	0.179	0.009	Yes
13	39	-0.350	0.009	752	-0.234	0.004	Yes
14	102	-0.030	0.013	611	0.110	0.009	Yes
15	28	-0.415	0.011	824	-0.301	0.004	Yes
16	11	-0.525	0.009	246	-0.405	0.006	Yes
17	9	-0.532	0.010	288	-0.471	0.006	Yes
All	518	-0.203	0.015	7017	-0.234	0.004	Yes

The above analysis suggests there is indeed a significant difference, indicating pedestrians walking as part of a group do have their walking speeds slowed.

6.4.4 Affects on Speeds due to Pedestrians having to make Deviations

A t-test was carried out to highlight whether deviations due to any reason can affect walking speed.

This involved aggregating the data on deviations due to other pedestrians with deviations as a result of other reasons.

The analysis is presented in Table 6.8 below.

Table 6.8: Results of T-Tests on Deviations

Data Set	Deviations			Non Deviations			Significant at the 5% level
	Obs.	Mean	Standard Error Mean	Obs.	Mean	Standard Error Mean	
1	8	-0.418	0.027	105	-0.090	0.026	Yes
2	3	-0.380	0.054	134	-0.106	0.028	Yes
3	2	-0.398	0.007	95	-0.094	0.025	Yes
4	23	-0.053	0.027	368	0.096	0.012	Yes
5	29	-0.019	0.024	447	0.083	0.010	Yes
6	83	-0.384	0.007	486	-0.305	0.005	Yes
7	20	-0.606	0.006	297	-0.478	0.005	Yes
8	42	-0.594	0.007	737	-0.470	0.003	Yes
9	64	-0.660	0.006	838	-0.536	0.003	Yes
10	1	-0.033	n/a	92	0.095	0.030	n/a
11	3	-0.346	0.065	96	-0.148	0.025	No
12	30	0.046	0.028	622	0.166	0.009	Yes
13	118	-0.325	0.006	660	-0.222	0.004	Yes
14	73	-0.032	0.016	639	0.105	0.008	Yes
15	130	-0.396	0.006	722	-0.288	0.004	Yes
16	23	-0.512	0.011	234	-0.400	0.006	Yes
17	50	-0.576	0.006	247	-0.451	0.006	Yes
All	840	-0.346	0.011	6695	-0.217	0.004	Yes

The above suggests there is a significant correlation between walking speeds and pedestrians having to make deviations (for whatever reason), although it was noted the sample size in Data Sets 2, 3, 10 and 11 are quite low. No suitable sample size was obtained from data set 10.

6.4.5 The Age of a Pedestrian

To examine the effect of age on walking speeds, an ANOVA test was undertaken to see if age affects a pedestrians walking speed. Age was ascertained subjectively, by visual inspection. From the analysis it is suggested that there is a significant relationship and the comparisons of the different age groups is given in Table 6.9 and depicted in Figure 6.7.

Table 6.9: ANOVA Multiple Comparisons of Speed with Age

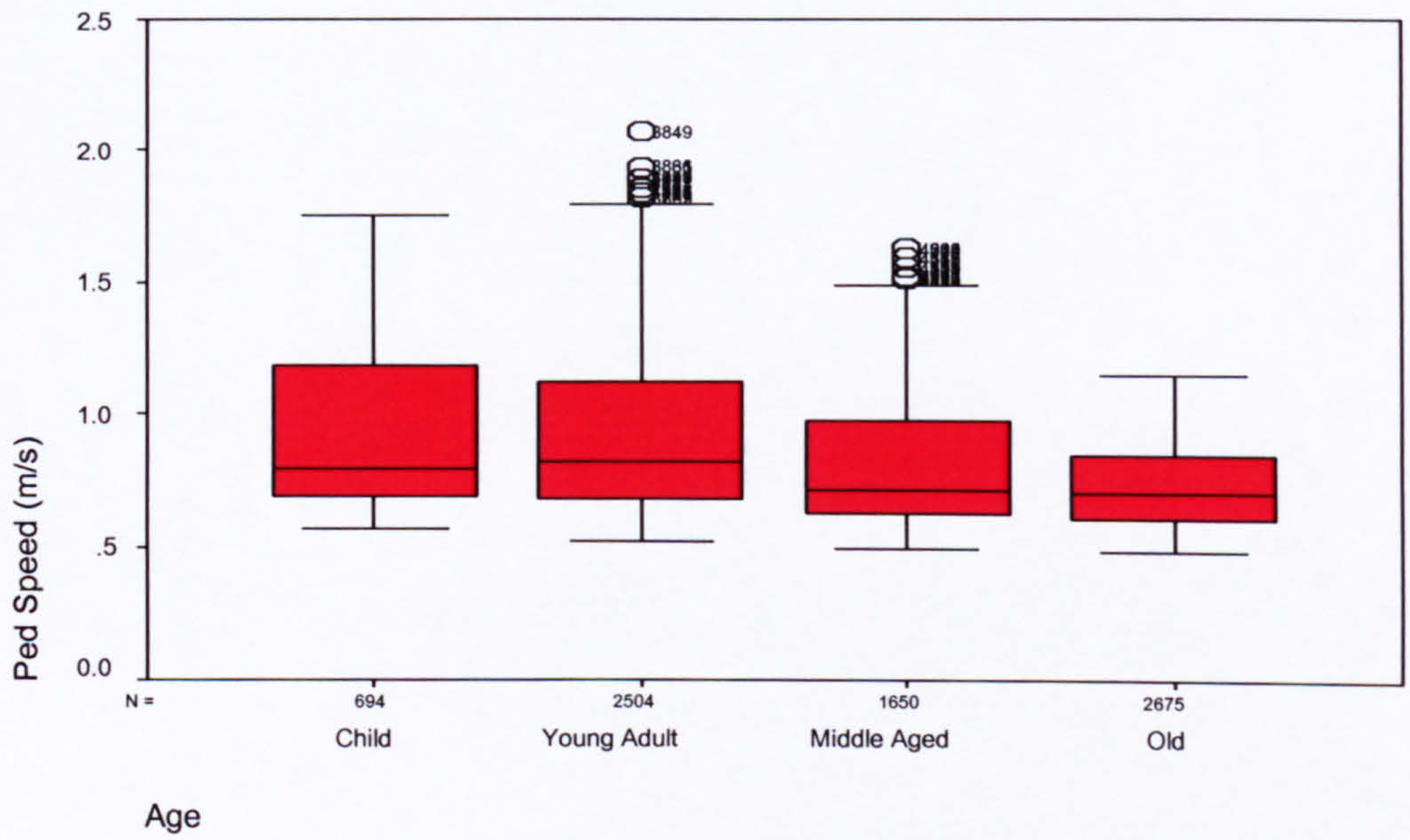
Multiple Comparisons

Dependent Variable: INV_SPD
Tukey HSD

(I) Age (1=C, 2=YA,3=MA, 4=O)	(J) Age (1=C, 2=YA,3=MA, 4=O)	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-1.6133E-02	1.421E-02	.668	-5.2637E-02	2.037E-02
	3	-.1510*	1.499E-02	.000	-.1895	-.1125
	4	-.2403*	1.411E-02	.000	-.2765	-.2040
2	1	1.613E-02	1.421E-02	.668	-2.0370E-02	5.264E-02
	3	-.1348*	1.051E-02	.000	-.1618	-.1078
	4	-.2241*	9.216E-03	.000	-.2478	-.2004
3	1	.1510*	1.499E-02	.000	.1125	.1895
	2	.1348*	1.051E-02	.000	.1078	.1618
	4	-8.9294E-02*	1.037E-02	.000	-.1159	-6.2643E-02
4	1	.2403*	1.411E-02	.000	.2040	.2765
	2	.2241*	9.216E-03	.000	.2004	.2478
	3	8.929E-02*	1.037E-02	.000	6.264E-02	.1159

*. The mean difference is significant at the .05 level.

Figure 6.7: Boxplot of the Variation of Pedestrian Speed with Age



This shows pedestrian walking speed decreases with age as one would anticipate. Applying one-way analysis of variance to the inverse of pedestrian speed reveals that children do not differ significantly from young adults but all other groups differ significantly.

6.4.6 Carrying Baggage or Luggage

One would expect the carrying of baggage or luggage would affect the walking speed of a pedestrian, and therefore a t-test was undertaken to explore this (see Table 6.10).

Table 6.10: Results of T-Tests on Carrying Baggage or Luggage

Data Set	Carrying Bags/Luggage			Not Carrying Bags/Luggage			Significant at the 5% level
	Obs.	Mean	Standard Error Mean	Obs.	Mean	Standard Error Mean	
1	9	-0.456	0.041	104	-0.084	0.026	Yes
2	12	-0.421	0.033	125	-0.083	0.023	Yes
3	4	-0.470	0.022	93	-0.084	0.025	Yes
4	136	-0.087	0.011	255	0.180	0.012	Yes
5	180	-0.073	0.010	296	0.168	0.010	Yes
6	227	-0.407	0.004	342	-0.256	0.005	Yes
7	101	-0.554	0.006	216	-0.454	0.006	Yes
8	258	-0.547	0.004	521	-0.441	0.004	Yes
9	218	-0.649	0.004	684	-0.511	0.003	Yes
10	8	-0.311	0.008	85	0.131	0.030	Yes
11	6	-0.363	0.067	93	-0.140	0.026	Yes
12	238	-0.009	0.008	414	0.257	0.010	Yes
13	308	-0.335	0.003	483	-0.178	0.004	Yes
14	244	-0.081	0.008	469	0.180	0.009	Yes
15	305	-0.407	0.004	547	-0.247	0.004	Yes
16	100	-0.476	0.007	157	-0.369	0.007	Yes
17	77	-0.574	0.008	220	-0.437	0.006	Yes
All	2431	-0.339	0.006	5104	-0.183	0.005	Yes

As expected, the analysis suggests there is a significant difference between walking speeds and carrying baggage or luggage, with quite large proportions of pedestrians observed found to be carrying something.

6.4.7 Pedestrians Accompanied by Children or Animals

This t-test was undertaken to see if being accompanied by children or animals affects walking speed. The analysis is presented in Table 6.11 below.

Table 6.11: Results of T-Tests on Accompanied by Children or Animals

Data Set	With Kids or Animals			Without Kids or Animals			Significant at the 5% level	LOS
	Obs.	Mean	Standard Error Mean	Obs.	Mean	Standard Error Mean		
1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	C
2	6	-0.411	0.028	131	-0.099	0.023	Yes	D
3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	A
4	26	-0.060	0.026	365	0.098	0.011	Yes	D
5	43	-0.018	0.017	433	0.086	0.010	Yes	D
6	15	-0.447	0.016	554	-0.313	0.046	Yes	E
7	10	-0.599	0.009	307	-0.482	0.005	Yes	D
8	20	-0.610	0.003	759	-0.472	0.003	Yes	D
9	21	-0.663	0.009	881	-0.542	0.003	Yes	E
10	n/a	n/a	n/a	n/a	n/a	n/a	n/a	C
11	n/a	n/a	n/a	n/a	n/a	n/a	n/a	D
12	50	-0.010	0.016	602	0.174	0.009	Yes	B
13	17	-0.394	0.014	774	-0.236	0.004	Yes	C
14	49	-0.041	0.016	664	0.100	0.008	Yes	D
15	18	-0.457	0.012	834	-0.301	0.004	No	E
16	16	-0.527	0.007	241	-0.403	0.006	No	E
17	10	-0.567	0.013	287	-0.469	0.006	No	F
All	218	-0.252	0.019	7317	-0.231	0.004	Yes	D

The analysis suggests being accompanied by children or animals seems to affect pedestrian speeds, although most sample sizes are quite low. This is found in almost all the data sets.

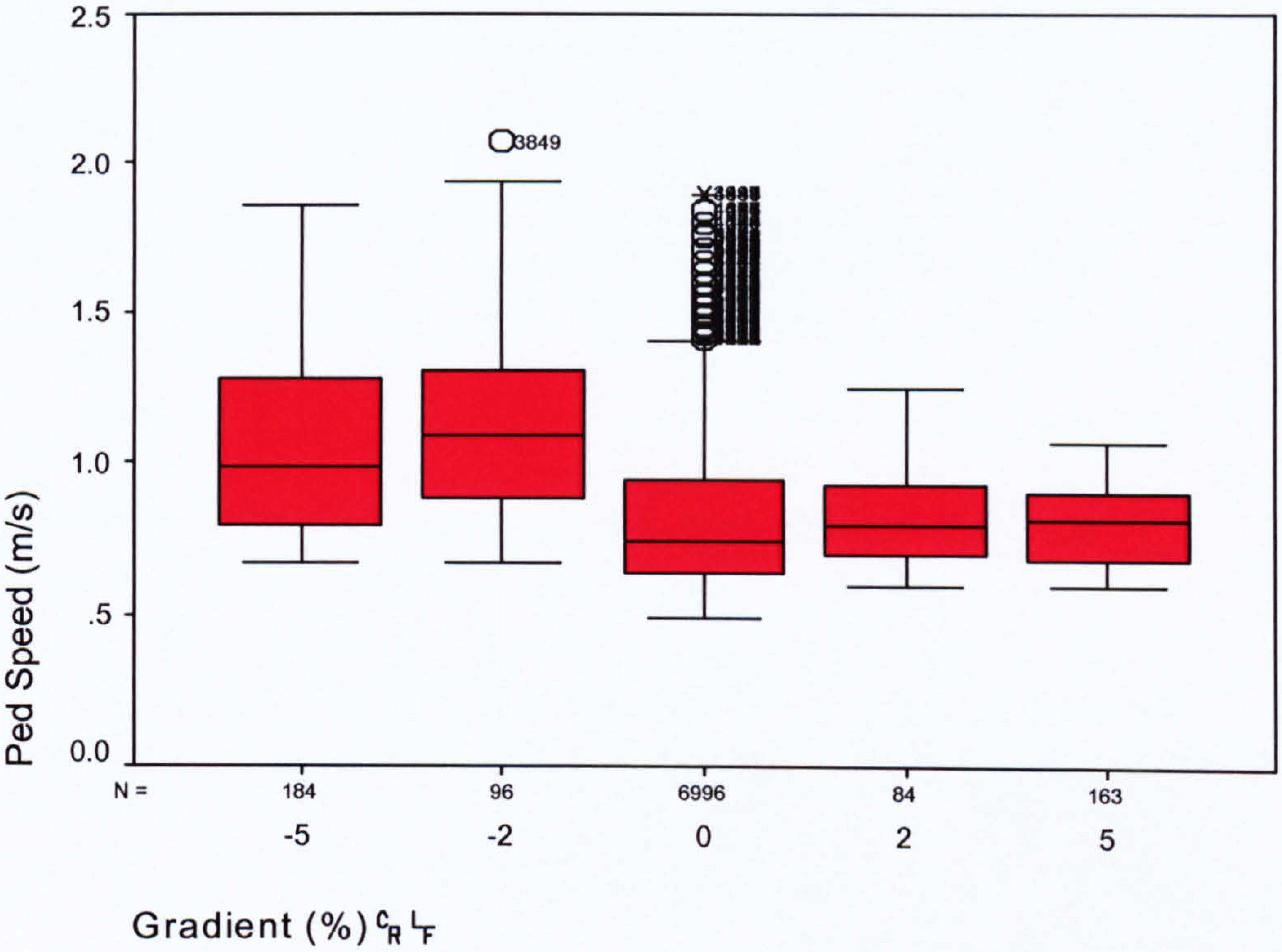
It was originally thought that walking with children or animals affects pedestrian speeds because of the need to walk at the same pace as the child or animal, and this becomes less significant as the levels of flow reach a point where the uniform walking speed of the groups of pedestrians slows to the same speed. However, the above results (which also shows a comparison with the relevant LOS ranges as an indication of the level of flow) suggest being accompanied by children or animals effects pedestrian speeds during most levels of flows.

6.4.8 Other Tests to Identify Variables which affect Walking Speeds

6.4.8.1 The Effect of Pavement Gradient on Walking Speed

The effect of pavement gradient on walking speed is displayed in Figure 6.8. It is apparent that pedestrian speed is quicker on negative gradients but is not significantly different on pavements with positive gradients when compared to level pavements.

Figure 6.8: The Effect of Pavement Gradient on Pedestrian Speed



6.4.8.2 Affects of Junctions

The presence of a junction within 10 metres is shown to significantly slow pedestrian speed (p =0.000) with a mean speed of 0.894 m/s when no junction is near falling to 0.772m/s when a junction is within 10 metres (an ANOVA test was applied to the inverse of pedestrian speed).

6.5 Predictive Models

6.5.1 The Need for the Development of Walking Speed Models

Section 2.3.2 of Chapter Two reviewed the most popular pedestrian analysis software packages commonly used to aid transport planners and engineers in the study and design of walking facilities and showed that they all have a common element: the concepts and techniques they use involve some sort of description of walking speed, pedestrian flow and/or crowd density, and how they relate to each other and interact with themselves or the surrounding area. These pedestrian simulation software packages are widely used in the estimation of flows and routes through an area and therefore developing infrastructure with suitable capacity to accommodate the expected volumes of demand, and their accuracy is dependent on a good prediction of walking speeds (Galea, 1997a; Cohen, 1997; Still, 2000; and Hoogendoorn, 2003).

Furthermore, the literature review showed that walking speed is a key requirement in almost all aspects of studying pedestrian movements. For example, when analysing pedestrian networks and their measures of effectiveness, Virkler (1996) noted that the HCM's arterial analysis chapter (11) uses overall average travel speed as the measure of effectiveness in determining LOS and therefore which geometric ranges should be used when developing suitable infrastructure. In addition, walking speed is also important when identifying suitable crossing times in the design of on-street crossings to safeguard pedestrians from motor vehicles (Dixon, 1996).

However, the initial analysis in Chapter Four showed the HCM methodology only represents just over half the factors that influence walking speed and highlighted the need for better predictive speed models.

This Section therefore presents the development of new models, in an attempt to predict pedestrian speed better than current methodologies.

Multivariate regression models were constructed from 80% of the data, with the remaining 20% being retained as a hold out sample to test the performance of the predictions.

Before presenting the models, Sections 6.5.2 and 6.5.3 explain the criteria adopted for selecting the best-fitting models and the structured approach followed to develop the models.

6.5.2 Model Criteria

Based on the findings of other research (e.g. Washington et al, 2003), four key criteria (comprehensiveness, quality of coefficients, explanatory power and the validity of the model assumptions) were used to guide model development and the final selection of the recommended models:

- **Comprehensiveness:** Successful models should contain reliable coefficients for as many relevant flow and other speed determinants as possible;

- **Quality of Coefficients:** A set of further criteria were used to assess whether a coefficient was of sufficient quality to warrant retention in the model. These included explanatory power, statistical significance (at the 95% confidence level), whether the coefficient was of the expected sign ('right signed'), the stability of the coefficient in different model formulations and the magnitude of the value of the coefficient;

- **Explanatory Power:** The extent to which the independent variables explain variations in speed (measured by the adjusted R^2 statistic). Whilst this is beneficial, it has generally been regarded as of lesser importance than obtaining a comprehensive and well-balanced model with robust coefficients (Washington et al, 2003); and

- **Validity of Model Assumptions:** The residuals (errors) should be normally and independently distributed.

6.5.3 Structured Approach to Model Development

The adopted criteria were used to guide the development of models. There were, however, a large number of potential explanatory variables and a structured approach to model development was therefore required. This comprised a five-stage development of final models:

- Stage A: Speed regressed against flow and/or density variables;
- Stage B: Addition of pedestrian characteristics variables to Stage A relationship(s);

- Stage C: Addition of geometric and walking environment variables to Stage B relationship(s);
- Stage D: Addition of variables describing the details of the survey (e.g. time periods, weather, etc) to Stage C relationship(s); and
- Stage E: Addition of adjacent land-uses variables to Stage D relationship(s).

In the first instance, potential explanatory variables were classified into five categories (flow or density, characteristics, geometry, survey conditions and adjacent land-uses).

The general analytical approach was then to explore alternative sets of explanatory variables from the first classification (flow and/or density). Having determined the best set(s) of flow and/or density variables, potential explanatory variables from the next classification (characteristics) were added. The best set of characteristic variables were then determined. A check was then undertaken to ensure that the quality of the flow coefficients was still satisfactory as the inclusion of additional variables may alter the size and significance of previous-entered variables.

The best set(s) of combined flow and/or density and characteristics variables were then augmented by geometry and walking environment variables and, in similar manner, by survey condition variables followed by adjacent land-uses variables. At each stage the variables entered at previous stages were checked for continued significance and stability of coefficient values. The analysis of pedestrian speed models followed the five-stage process outlined above.

6.5.4 Distribution of Walking Speeds

In order to satisfy the normality assumption to allow multivariate regression to be used, a check of the distribution of walking speeds was undertaken which showed pedestrian speed to be highly skewed as illustrated in Figure 6.9. Various transformations, including logarithmic, were examined and it was found that the most suitable transformation was the reciprocal of pedestrian speed (see Figure 6.10). Therefore, this was used as the dependent variable in developing the new statistical models.

Figure 6.9: Histogram of Pedestrian Speed on All Data Sets Combined

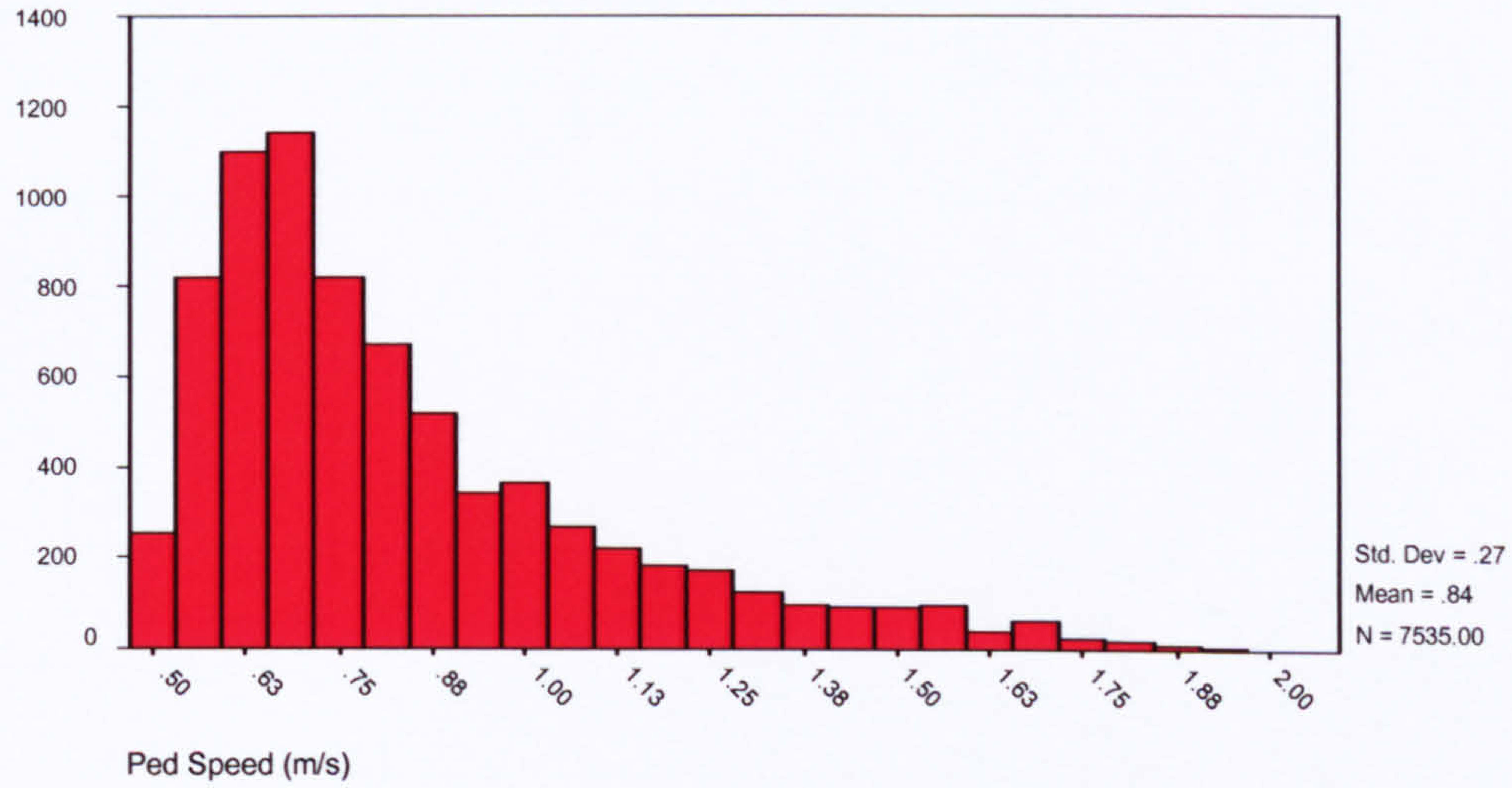
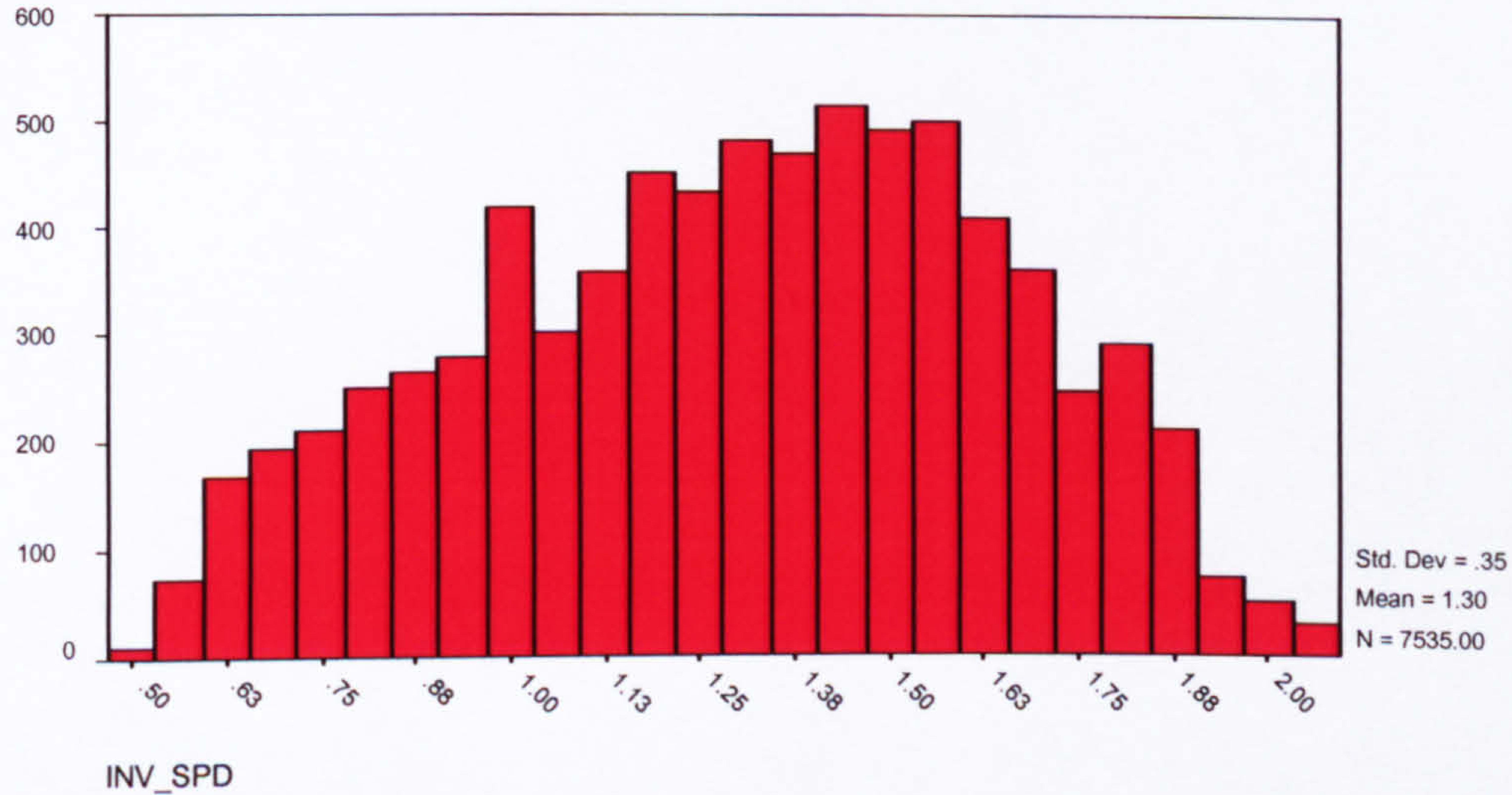


Figure 6.10: Histogram of Transformed Pedestrian Speed on All Data Sets



6.5.5 The Development of a Base Model

6.5.5.1 Base Model using Density as a Measure of Pedestrian Demand

The selection of the variables for inclusion into the model was based on adding variables identified in the literature review and expanded upon in Chapter Five, firstly by adding those variables within the control of the transport designer and then supplementing them with the rest of the variables in the exhaustive list.

Variables were selected using the subset modelling approach (Krzanowaski, 1998). If the best subset modelling identified any variable as being significant at the 5% level it was retained in the list of variables included in the model. The modelling also checked for multicolinearity and prevented entry of variables which were highly correlated with a variable in the model.

For pedestrian speed (or rather the reciprocal of pedestrian speed) the best-fit Base Model using density is displayed in Table 6.12. This was obtained using density as the main variable to represent the level of pedestrian demand. In keeping with the statistical rules for normal-shaped distribution in multivariate regression analysis, the square of density was also entered.

Table 6.12: Regression Coefficients for Base Model (using Density) of the Reciprocal of Walking Speed

Model Co-efficients	Unstandardised Coefficients		Standardised Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	0.988	0.018		55.738	0.000
Den_Centre (ped/m^2)	0.707	0.024	1.439	29.546	0.000
Den_Centre Squared	-0.120	0.008	-0.614	-15.842	0.000
Gradient (%)	0.02803	0.001	0.092	19.049	0.000
Junction	0.169	0.013	0.244	13.372	0.000
Bus_Stop	0.02936	0.014	0.042	2.121	0.000
Vehicles	-0.137	0.016	-0.156	-8.511	0.000
Medium_Age	0.129	0.004	0.153	29.147	0.000
Elderly	0.208	0.004	0.288	54.777	0.000
Bags	0.193	0.004	0.260	52.945	0.000
Peak	-0.156	0.007	-0.215	-20.868	0.000
Winter	-0.167	0.018	-0.244	-9.462	0.000
Rain	-0.157	0.006	-0.218	-28.078	0.000
Retail	-0.215	0.007	-0.162	-28.788	0.000
Offices	0.313	0.020	0.386	15.878	0.000

Note: dependent variable is the Inverse of Speed

The model fits with an adjusted R square of 86%. Of the variables it appears that Den_Centre and then Offices are most influential in affecting pedestrian speed. It is of note that some of the variables which were initially found to be highly correlated, such as Infirm or Child_Animal (i.e. being accompanied by a child or an animal), have been excluded. This suggests that, in the presence of other variables, they were not significant. This could be because of poor measurement of the relevant variable or the distribution of the effect was so changeable that it did not appear to be significant. The latter situation was not helped by the fact that there were relatively few observations of the variable Infirm. An alternative reason is that perhaps they were highly correlated with other variables, such as age. Where a variable was excluded for being correlated, it was decided to include the variable which was deemed to be measured most reliably and had the most observations.

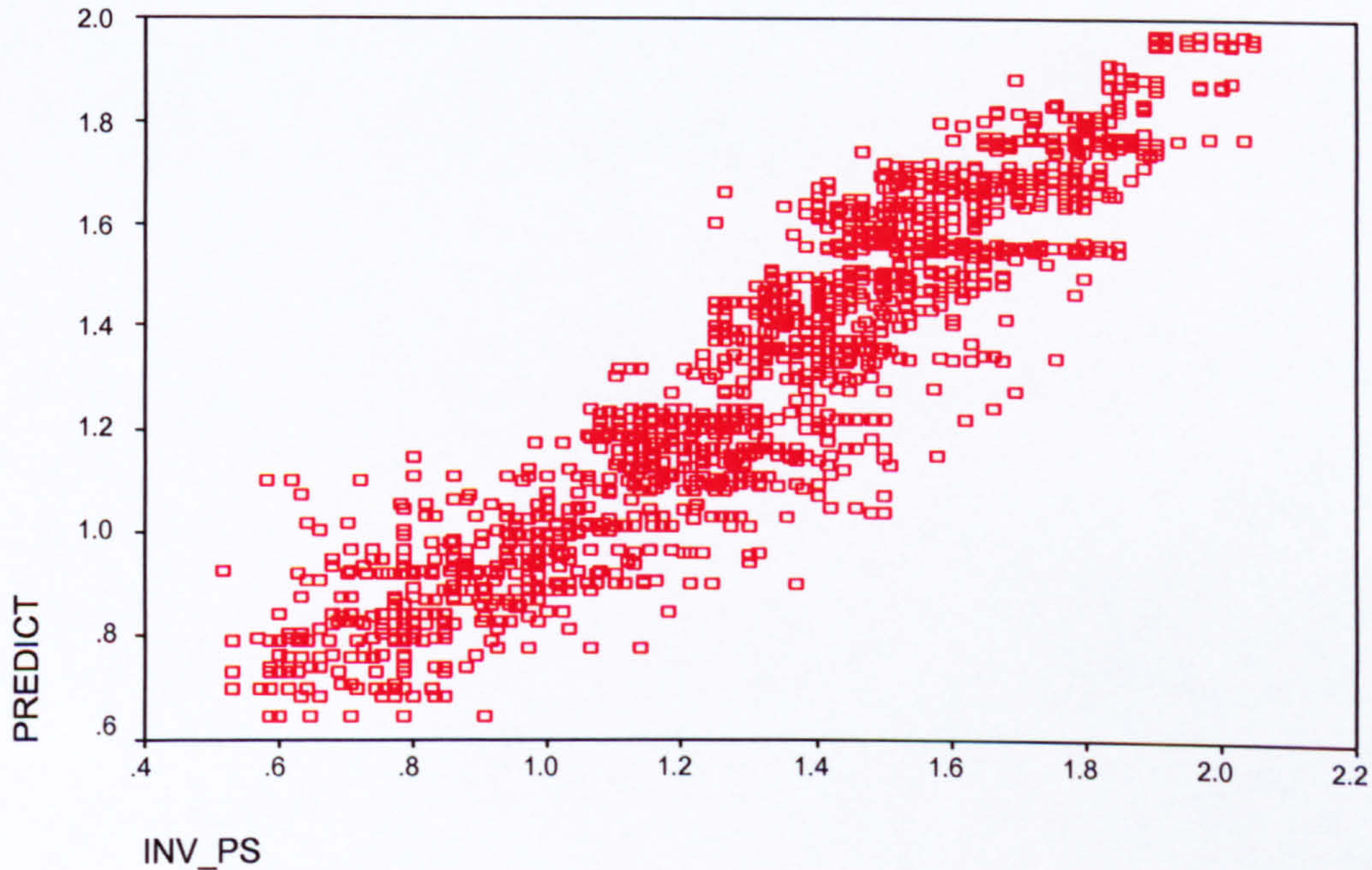
Of the other variables, Gender was not found to be significant in the exploratory analysis and this was confirmed by the model. The other variables (Guard_Rail, Furniture, Entrance_Exit, Bus_Lane, Stops, Group, Deviate, Houses, Vehicles, Parking and Weekday) where not found to be significant because their effects were dwarfed by the variables included which had a stronger correlation with walking speed.

Analysis of the residuals indicated that this was a satisfactory Base Model.

6.5.5.2 Validating against the Hold-Out Data

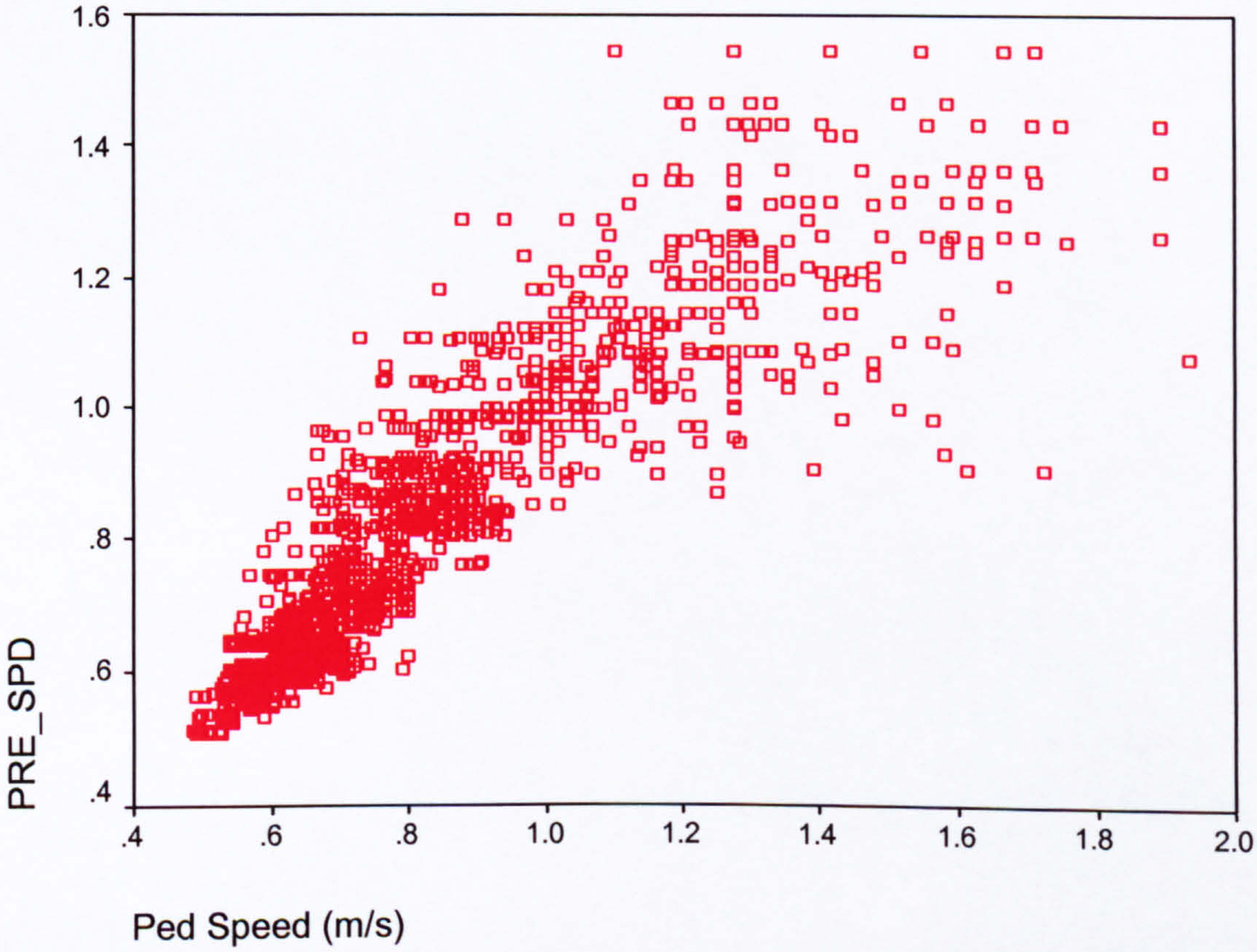
As explained above, the model was developed using 80% of the data, with the remaining 20% kept to test the predictive powers of the model. Figure 6.11 shows the results of using the model to predict the remaining 20% of cases.

Figure 6.11: Predicted Reciprocal of Walking Speed Plotted against Observed Data



The reciprocal of pedestrian speed was well predicted as can be observed from the prediction plotted against the observed as displayed in Figure 6.11. The Pearson correlation coefficient between the predicted and observed is 0.925 and the mean absolute percentage error (MAPE) is 8.6%. Inverting the predicted reciprocal to give pedestrian speed was also tested. However, this was found not to correlate as well as the previous, with the Pearson correlation coefficient dropping to 0.897 (although the MAPE deteriorates only slightly to 8.7%). From the pattern displayed in Figure 6.12, it is clear that the quality of the predictions are poorer for high speeds. This suggests the model performs better in high and medium ranged LOS's, but it is nevertheless the author's view that the predictions are acceptable during low LOS ranges.

Figure 6.12: Predicted Speed Plotted against Observed Pedestrian Speed



6.5.5.3 Adapting the Base Model to Incorporate Pedestrian Flow Ratio

The literature review showed that some analysts believe it is useful to incorporate the effects of the proportions of pedestrian flows in the analysis. This allowed the modelling to take account of potential frictional factors caused by oncoming pedestrians during high LOS ranges (e.g. Annesley et al, 1991; Harris, 1991) or the effects of weaving through crowds (Still, 2000).

To allow for this, a new term was computed to reflect the ratio of pedestrian flows and added to the Base Model. This was calculated as follows:

Flow Ratio = (With Flow – Against Flow) / Total Flow

Where
Flow Ratio = ratio of flows;
With Flow = pedestrian flow travelling in the main direction of flow;
Against Flow= pedestrian flow travelling in the minor direction of flow (against the main); and
Total Flow = total two-way pedestrian flow (=With Flow + Against Flow).

The revised model gave the following coefficients shown in Table 6.13.

Table 6.13: Regression Coefficients for Base Model (using Density) Incorporating Ratio of Flows

Model Co-efficients	Unstandardised Coefficients		Standardised Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	0.989	0.018		55.754	0.000
Den_Centre (ped/m^2)	0.707	0.024	1.438	29.523	0.000
Den_Centre Squared	-0.120	0.008	-0.614	-15.823	0.000
Gradient (%)	0.02799	0.001	0.092	19.018	0.000
Junction	0.169	0.013	0.244	13.378	0.000
Bus_Stop	0.02939	0.014	0.042	2.123	0.000
Vehicles	-0.137	0.016	-0.156	-8.511	0.000
Medium_Age	0.128	0.004	0.153	29.118	0.000
Elderly	0.208	0.004	0.288	54.754	0.000
Bags	0.193	0.004	0.261	52.961	0.000
Peak	-0.156	0.007	-0.215	-20.869	0.000
Winter	-0.167	0.018	-0.224	-9.468	0.000
Rain	-0.157	0.006	-0.218	-28.082	0.000
Retail	-0.215	0.007	-0.162	-28.801	0.000
Offices	0.312	0.020	0.386	15.869	0.000
Flow Ratio	0.01119	0.009	0.006	1.221	0.222

Note: dependent variable is the Inverse of Speed

This fitted with an adjusted R-square of 87%. From the standardised coefficients it is apparent that Density is the most influential variable. The inclusion of the ratio of pedestrian flows in this model correlates reasonably well with the hold out sample (r = 0.902) and the MAPE for these predictions is 8.5%. Although the predictive powers of this revised model have improved, they have improved marginally. This suggests the ratio of the pedestrian flows is not as statistically significant compared to the other parameters.

6.5.6 Classification of Base Model Variables

6.5.6.1 Three Groups of Variables

The Base Models use variables which include pedestrian density, pedestrian age, time of day, whether or not it rains, and the geometric characteristics and type of environment the walkway is located in. Those variables shown to significantly influence walking speed can be divided into three groups, depending on the ease with which transport planners and engineers can influence (Group 1 being the most easy through to Group 3 which is virtually impossible to influence):

- Group 1 variables significantly influencing walking speed
    - density (something designers can alter by varying the lengths and widths of the walkway);
    - gradient;
    - proximity of junctions;
    - presence and/or proximity of bus stops and/or lanes; and
    - presence and/or proximity of cars and other motorised traffic.

- Group 2 variables significantly influencing walking speed
    - presence and/or proximity of retail buildings; and
    - presence and/or proximity of office buildings.

- Group 3 variables significantly influencing walking speed
    - age of pedestrian;
    - time of travel (e.g. peak or off-peak time of the day);
    - seasonal variations (e.g. winter or summer);
    - carrying baggage or luggage; and
    - presence of rain.

Classifying the variables in the above three groups shows there are 12 variables in total. Five of them can easily be influenced by transport designers, and a further two are also possibly influenced by the planning process (although not straightforward).

However, the inclusion of all these variables has yielded better performing models than those prepared using current industry-standard variables obtained from the initial analysis presented in Chapter Four.

This suggests the use of these models will help transport planners and engineers predict the level of service of walkways for different mixes of conditions, environments and type of pedestrians.

6.5.6.2 Base Models exclusively for Design Orientated (Group 1) Variables

It is acknowledged that sufficient data might not always be available to use the best-fit models identified in this Chapter. In addition, it is acknowledged that only those variables identified in Group 1 are readily within the control of the transport planner and engineer. To allow for this, two variations of the Base Models were developed using only those variables in the designer's control (Group 1). The first used density to represent the level of pedestrian demand and the second included the ratio of the directional flows. They were named the Group 1 Base Models.

The best-fitting Group 1 Base Model using density as a measure of the level of pedestrian demand is displayed in Table 6.14. This was obtained using density as the main variable to represent the level of pedestrian demand. As with the Full Base Models, in keeping with the statistical rules for normal-shaped distribution in multivariate regression analysis, the square of density was also entered.

Table 6.14: Regression Coefficients for the Group 1 Base Model (without Flow Ratio)

Model Co-efficients	Unstandardised Coefficients		Standardised Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	0.679	0.011		59.815	0.000
Den_Centre (ped/m^2)	0.908	0.022	1.849	42.188	0.000
Den_Centre Squared	-0.225	0.007	-1.149	-30.080	0.000
Gradient (%)	0.02711	0.002	0.089	11.855	0.000
Junction	0.07424	0.009	0.107	8.086	0.000
Bus_Stop	-0.0477	0.013	-0.068	-3.595	0.000
Vehicles	0.09323	0.015	0.106	6.341	0.000

Note: dependent variable is the Inverse of Speed

This model fitted with an adjusted R-square of 79%. Testing the model using the 20% hold-out data gave a Pearson correlation coefficient of 0.699 and a prediction M.A.P.E. of 23.2%.

It is noted that, unlike the Full Base Models, the variable Vehicles has been included in this model. This variable could also act as a proxy for and reflect other variations in the street environment. One would anticipate vehicle flow to be different in relation to differing street environments, and the presence of other variables such as Offices and Retail in the Full Base Models are likely to be highly correlated with the Vehicles variable which explains its exclusion in the Full Base Model and inclusion here.

Excluded variables were excluded for the same reasons as discussed after Table 6.12.

Adapting the Group 1 Base Model to incorporate pedestrian flow ratio, gave the best-fitting model displayed in Table 6.15.

Table 6.15: Regression Coefficients for the Group 1 Base Model (with Flow Ratio)

Model Co-efficients	Unstandardised Coefficients		Standardised Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	0.679	0.011		59.824	0.000
Den_Centre (ped/m^2)	0.908	0.022	1.848	42.159	0.000
Den_Centre Squared	-0.225	0.007	-1.148	-30.065	0.000
Gradient (%)	0.02706	0.002	0.089	11.830	0.000
Junction	0.07437	0.009	0.107	8.100	0.000
Bus_Stop	-0.0473	0.013	-0.067	-3.570	0.000
Vehicles	0.09292	0.015	0.106	6.319	0.000
Flow Ratio	0.01519	0.014	0.008	1.063	0.288

Note: dependent variable is the Inverse of Speed

This model fitted with an adjusted R-square of 80%. Testing the model using the 20% hold-out data gave a Pearson correlation coefficient of 0.703 and a prediction M.A.P.E. of 22.9%.

It is satisfying that the model incorporating the ratio of the directional flows gave similar predictive ability suggesting the model performs well, although it is not as accurate as the full model.

6.5.7 Suitable Ranges of Variables in the New Base Models

It is important to realise that the new Base Models were developed using data collected from a sample of surveys. Although it is the authors view this data is very comprehensive and covers most travel conditions (including all LOS ranges), the new Base Models are based on data with known ranges and characteristics. In particular, some of the key variables might only produce suitable estimates within the ranges of the relevant data. The suitable ranges of the key variables of the new models are shown in Table 6.16.

Table 6.16: Ranges of the Key Variables of the New Base Models

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	7,535	7,535	7,535	7,535	7,535	7,535	7,535
Mean	8.248	40.473	12.336	1.957	21.063	0.836	164.594
Std. Dev	2.068	15.231	4.642	1.452	15.633	0.275	54.037
Minimum	2.700	9.524	2.903	0.361	3.886	0.488	96.063
Maximum	12.300	112.941	34.424	7.500	80.732	2.069	407.283

Other variables used in the new models do not require measurements of absolute values, because they are dummy variables which are either 1 or 0 (e.g. 1 for elderly else 0, etc).

6.5.8 Sensitivity of the Key Variables

A series of calculations were undertaken using the new Base Model developed (shown in Section 6.5.3.2 and Table 6.14) to ascertain the relative sensitivities of the key variables in Group 1. The Group 1 variables were selected because they are in the designer's control. Similar sensitivity tests on the model developed using the HCM methodology were also undertaken, to compare against the results of the new model.

The analysis undertaken can be summarised as follows:

- walkway width (which affects density) was increased and decreased by increments +/- 0.5m;
- gradient was increased and decreased by increments +/- 0.5%;
- with and without the presence of a junction within 10 metres of the walkway;
- with and without the presence of vehicular traffic (cars) adjacent to the walkway; and
- with and without the presence of a bus lane adjacent to the walkway.

Apart from the variables described above, no other variables were changed.

6.5.8.1 Sensitivity Tests on Walkway Width and Gradient

The results of the Sensitivity Tests on Walkway Width and Gradient are shown in Table 6.17.

Table 6.17: Results of the Sensitivity Tests on Walkway Width and Gradient

		-2.5	-2.0	-1.5	-1.0	-0.5	0	0.5	1.0	1.5	2.0	2.5
New Model	Walkway Width	n/a	-439%	-146%	-54%	-17%	0%	9%	13%	16%	17%	18%
	Gradient	2.1%	1.7%	1.3%	0.8%	0.4%	0%	-0.4%	-0.8%	-1.3%	-1.7%	-2.1%
HCM Methodology	Walkway Width	n/a	-279%	-93%	-34%	-11%	0%	6%	13%	29%	67%	151%
	Gradient	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Gradient is not used in the HCM methodology, so no comparison could be made. The results of the analysis using the new Group 1 Base Model show gradient has a symmetrical affect on walking speed. The results indicate that for every +/- 0.5% change in gradient there would be about a -/+ 0.4% change to walking speed. This is to be expected, as positive gradients mean pedestrians have to walk upwards. The steeper the gradient the slower speed becomes.

The effects on walkway width are much more significant, and effect both the new Group 1 Base Model and the model derived from the HCM methodology. The results of the analysis using the new Group 1 Base Model show as walkway width increases it has a less profound impact on walking speed. This is to be expected given this is directly related to the LOS range (a higher increase in walkway width would mean a lower LOS range, relieving walking conditions until they reach free-flow travelling). Similarly, as walkway width reduces it constricts the walking area and hence increases the LOS range. This, however, seems to have an exponential affect on reducing walking speeds, although this is also as one would expect.

The results of the analysis using the model derived from the HCM methodology show a significantly different reaction to the affects of walkway width, with a much larger impact on walking speed as walkway width increases. This suggests that estimates of walking speeds at lower LOS ranges are much higher than comparable estimates from the new model. As walkway width reduces (creating denser LOS ranges), the HCM methodology produces lower estimates of walking speeds than similar estimates from the new model. The effects on walking speeds are not symmetrical, however, with reductions in walkway width having a greater impact on speeds than increases.

6.5.8.2 Sensitivity Tests on the Other Variables

The results of the Sensitivity Tests on whether or not there is the presence of a junction within 10 metres of the walkway showed that speeds estimated by the new model decrease by about 8% without the presence of a junction. This is to be expected, since there could be affects due to interaction with other pedestrians waiting at the junctions or coming from other approaches of the junction. The presence of a junction within 10 metres of the walkway is not used in the HCM methodology, so no comparison could be made.

The results of the Sensitivity Tests on whether or not there is the presence of vehicular traffic (cars) adjacent to the walkway showed that speeds estimated by the new model decrease by about 6.5% with the presence of vehicular traffic. This confirms the findings of the literature review which showed the presence of vehicular traffic has a significant affect, and that lightly trafficked areas (including traffic calmed areas) have a positive affect on walking speeds. The presence of vehicular traffic (cars) adjacent to the walkway is not used in the HCM methodology, so no comparison could be made.

The results of the Sensitivity Tests on whether or not there is the presence of a bus lane adjacent to the walkway showed that speeds estimated by the new model increase by about 4% when there is the presence of a bus lane. This could be related to the previous findings, and the bus lane could be viewed as being some sort of 'buffer area' between pedestrians and free-flowing vehicular traffic. The presence of a bus lane adjacent to the walkway is not used in the HCM methodology, so no comparison could be made.

6.6 Discussion

The graphical comparisons of the new data against the figures in the previously developed relationships have shown that the new data collected for use in this thesis is satisfactorily replicating them. The new data showed similar walking characteristics as expected from pedestrians. This provided confidence that the new data has been processed in line with industry-standards.

Tests undertaken on the HCM methodology showed that it only described about two thirds of the variables that influence walking speeds indicating there are more factors which influence pedestrian speeds (not just flow and space). This finding was almost identical to that found from the initial pilot study undertaken on a walkway in a shopping area in Edinburgh and confirmed the following:

- expanding the available cases did not improve the predictive power of the HCM methodology;
- the hypothesis that more variables should be used to improve the estimation of walking speed was not disproved. Many variables were shown to significantly influence walking speeds. These additional variables were found to belong to three groups of classifications. This seems to corroborate the Research Hypotheses in Chapter Five. Surprisingly, however, gender was not found to be an important determinant of walking behaviour;
- the HCM methodology as it currently stands is not fully applicable to the types of walking environments that are the subject of this research (on-street walkways in UK shopping and Central Business areas);

- a set of new statistical models were developed which encompassed more variables than are currently used by the HCM methodology;
- these new models have better predictive powers than the HCM methodology and explain more of the variables that influence walking speeds; and
- further versions of the new models were constructed to include the effects of the ratio of directional flows. These models gave slightly better explanatory power and can be used, although require more data.

These findings corroborate the conclusions from the literature review and the pilot study. It is advocated that these new models should be incorporated into pedestrian studies.

6.7 Concluding Remarks

Presented in this Chapter are the findings of various statistical tests which identified key variables which have a significant affect on walking speeds. These key variables were then used to develop the new models to improve the prediction of walking speeds. A series of best-fit models were found and the variables required to use the new models can be categorised into three Groups, representing the different levels of influence designers have on each variable. The results of the initial validation of the new models have shown them to have strong predictive capabilities. However, there is a need to undertake further validation using an independent set of data so as to ensure the new models' goodness-of-fit is not a one-off incident but rather a genuine indication of their potential. This is explored in Chapter Seven.

7 MODEL VALIDATION

7.1 Introduction

One of the primary objectives of this research was to validate the developed models against an independent set of data. Although the models developed in Chapter Six were prepared using only 80% of the data collected and checked against the remaining 20% hold-out data, it was considered that comparing and testing against an independent set of data should be undertaken so as to ensure the models' goodness-of-fit to further verify the models.

Presented in this Chapter are the results of the model's validation and tests. The Chapter begins by explaining the process used for validation, and the reasons for its selection, before setting out a series of comparisons of estimates from the new model against a series of independent observations. A number of statistical tests are then presented showing the goodness-of-fit of the models' forecasts. The Chapter then concludes with a discussion on the findings and their implications for pedestrian modelling.

7.2 The Validation Process

7.2.1 Technique

The technique used in the validation process was based on the research and subsequent recommendations of Naderi and Raman (2002). This involved estimating walking speeds using some of the new models developed in Chapter Six against a set of independent observations.

In addition, another set of estimates based on the Highway Capacity Manual (HCM) methodology was obtained from an existing pedestrian computer model developed as part of an actual pedestrian planning study. This allowed comparisons between the new models to be made against the HCM methodology, using a series of statistical tests carried out to ascertain the goodness-of-fit of the models.

7.2.2 Models used for Validation

Of the new statistical models presented in Chapter Six, two were selected for this validation exercise. These were the Base Model as shown in Table 6.12 from Section 6.5.5.1 and the Group 1 Base Model as shown in Table 6.14 from Section 6.5.6.2. The Group 1 Base Model is a sub-set of the full Base Model, and includes only those variables identified as being readily within the control of the transport planner and engineer.

These were chosen because:

- the data required to use these models was readily available, whereas the other models required more data which was not available;

- the other models in Chapter Six incorporate the ratio of directional pedestrian flows. This is the only difference between them and the Base Model and the Group 1 Base Model, however density is a key variable in the two base models and density is a function of pedestrian flow;

- it is considered the base models have significantly better predictive powers than the existing HCM methodology, even without the inclusion of variables representing the ratio of directional flows; and

- the models incorporating flow ratios perform only slightly better than the base models. This also means that if the validation of the base models shows they have better predictive powers than the HCM methodology, then the other new models should produce better validation results.

7.2.3 The Software Used

7.2.3.1 Description

To aid in the validation process, an existing computer software modelling program was used. As mentioned in Section 7.2.1 above, this was developed as part of an actual pedestrian planning study. Use of an existing software program that is widely used in pedestrian modelling was considered advisable because it ensures consistency in the calculation of walking speeds using the HCM methodology and the new models.

The pedestrian software used for this validation was a PEDROUTE model developed by the Halcrow Group (Halcrow, 2000 and Halcrow, 2002c). A version of the software was programmed for a study of walking conditions and pedestrian movements for a section of the centre of Edinburgh. Pedestrian movement surveys were undertaken in 1999 over several weeks during April and November to take cognisance of seasonal variations (Halcrow, 2000). The PEDROUTE model was developed primarily using this data, however the model has been recently updated using further surveys undertaken in 2001 (Halcrow, 2002c). Displayed in Appendix Four are extracts from the model.

7.2.3.2 Calculating Estimates of Walking Speeds

All estimates of walking speeds were carried out using the PEDROUTE software, to ensure consistency in the estimation process. The reasons for selecting the PEDROUTE model are discussed in Section 7.2.3.5 below.

As explained in the literature review in Chapter Two, PEDROUTE uses a mathematical speed/density relationship based on the HCM methodology. This was replaced with the new mathematical models selected for validation, as shown in Section 7.2.2. The estimates of walking speeds based on the HCM standards were those already produced by the PEDROUTE model.

7.2.3.3 Output Produced

Undertaken in the PEDROUTE model is an analysis over a peak period of demand, when the network is likely to be at its most vulnerable. Halcrow have developed the model to analyse conditions during the evening peak hour, defined as between 17:00 to 18:00 hours. The data collected was over this period for a Thursday, during the months and years mentioned in the previous Section.

To allow for a more refined analysis, the PEDROUTE model was set up to analyse the peak hour in a series of time-slices. The peak hour was divided into 15-minute time-slices with appropriate pedestrian flows identified for each time-slice. The model then analyses each time-slice, with the results from the first time-slice feeding into the analysis of the second, and so on.

7.2.3.4 Outputs Used for this Validation

Independent observations were undertaken by Halcrow on 11 walkways in the pedestrian network, for use in the calibration of the PEDROUTE model (Halcrow, 2002c). This data included observed pedestrian spot-counts and speeds, over each of the 15-minute time-slices on each of the 11 walkways. These were then averaged to give mean observed walking speed, for each time-slice on each walkway.

This was used in this validation to compare the observed mean walking speeds versus the estimates. Since there are 11 walkways with 4 time-slice observations, this gave a total of 44 observations to compare against estimates.

7.2.3.5 Reasons for using the PEDROUTE Model

The PEDROUTE model was selected for this validation exercise because:

- PEDROUTE is widely used in pedestrian modelling and using the software helped ensure consistency in the calculation of walking speeds based on the HCM methodology and the new models;

- the site in Edinburgh used to collect data for developing the new pedestrian models in Chapter Six is included in the study area used by Halcrow to develop the PEDROUTE model;

- the data used in the development of the Halcrow PEDROUTE model was obtained during similar seasons (Spring and Winter) and over similar years (1999 to 2001) as the data obtained for the development of the new pedestrian models; and

- the Halcrow PEDROUTE model was produced independently of this research, and has been audited (see Halcrow, 2002c) and used in various transport studies. It has recently been updated and re-calibrated.

7.4 Details of the Observed Data

Table 7.1 shows a summary of the observed data collected by Halcrow and used in the validation of the various models. Also shown are the averages for the total modelled period.

Table 7.1: Summary of the Observed Data

N	Walkway	Time Slice	Flow	LOS	Obs Speed
1	1	17:00 - 17:15	34	B	1.23
2	2	17:00 - 17:15	41	B	1.20
3	3	17:00 - 17:15	93	D	0.90
4	4	17:00 - 17:15	79	D	0.97
5	5	17:00 - 17:15	52	C	1.15
6	6	17:00 - 17:15	5	A	1.33
7	7	17:00 - 17:15	61	C	1.11
8	8	17:00 - 17:15	16	A	1.31
9	9	17:00 - 17:15	21	A	1.30
10	10	17:00 - 17:15	85	D	0.92
11	11	17:00 - 17:15	27	A	1.27
12	1	17:15 - 17:30	38	B	1.17
13	2	17:15 - 17:30	46	B	1.14
14	3	17:15 - 17:30	105	E	0.86
15	4	17:15 - 17:30	89	D	0.90
16	5	17:15 - 17:30	59	C	1.09
17	6	17:15 - 17:30	6	A	1.26
18	7	17:15 - 17:30	69	C	1.05
19	8	17:15 - 17:30	18	A	1.24
20	9	17:15 - 17:30	24	A	1.24
21	10	17:15 - 17:30	96	D	0.87
22	11	17:15 - 17:30	30	B	1.21
23	1	17:30 - 17:45	40	B	1.11
24	2	17:30 - 17:45	48	B	1.08
25	3	17:30 - 17:45	109	E	0.81
26	4	17:30 - 17:45	93	D	0.86
27	5	17:30 - 17:45	61	C	1.04
28	6	17:30 - 17:45	6	A	1.30
29	7	17:30 - 17:45	72	D	1.00
30	8	17:30 - 17:45	19	A	1.18
31	9	17:30 - 17:45	25	A	1.17
32	10	17:30 - 17:45	100	E	0.73
33	11	17:30 - 17:45	32	B	1.14
34	1	17:45 - 18:00	37	B	1.19
35	2	17:45 - 18:00	45	B	1.16
36	3	17:45 - 18:00	102	E	0.83
37	4	17:45 - 18:00	87	D	0.92
38	5	17:45 - 18:00	57	C	1.11
39	6	17:45 - 18:00	6	A	1.29
40	7	17:45 - 18:00	67	C	1.09
41	8	17:45 - 18:00	18	A	1.27
42	9	17:45 - 18:00	23	A	1.26
43	10	17:45 - 18:00	94	D	0.89
44	11	17:45 - 18:00	30	B	1.23
Averages			**51**	**C**	**1.10**

7.5 Comparison of Results

7.5.1 Statistical Tests of the Estimated Speeds versus Observed Speeds

This section compares the estimates of walking speeds from the various models against the independently observed data.

Statistical tests including percentage differences, mean absolute errors (MAE), route mean square errors (RMSE) and Chi-square tests are presented in Table 7.2.

Table 7.2: Summaries of the Statistical Tests

Tests	New Models		Existing Model
	Base Model	**Base Model using only Group 1 Variables**	**HCM**
Average Error (%)	7.8%	15.6%	21.2%
MAE	0.09	0.17	0.39
MAPE	7.0%	13.0%	33.1%
MSE	0.01	0.03	0.19
RMSE	0.09	0.19	0.43
Chi-square	0.30	1.11	6.06
Pearson Correlation Coefficient (between predicted and observed)	0.99	0.97	0.94

Table 7.3 shows a direct comparison of the estimates obtained from the new base models and the HCM methodology against the observed data.

Table 7.3: **Comparison of Estimates from the Models**

N	Observed Speed	New Models				Existing Model	
		Base Model	Diff %	Base Model using Group 1 Variables	Diff %	HCM	Diff %
1	1.23	1.33	8.13%	1.43	16.26%	1.51	22.76%
2	1.20	1.31	9.17%	1.42	18.33%	1.50	25.00%
3	0.90	0.96	6.67%	1.02	13.33%	0.56	-37.78%
4	0.97	1.05	8.25%	1.13	16.49%	0.57	-41.24%
5	1.15	1.20	4.35%	1.25	8.70%	1.31	13.91%
6	1.33	1.42	6.77%	1.51	13.53%	1.90	42.86%
7	1.11	1.15	3.60%	1.19	7.21%	1.55	39.64%
8	1.31	1.41	7.63%	1.51	15.27%	1.99	51.91%
9	1.30	1.40	7.69%	1.50	15.38%	1.93	48.46%
10	0.92	0.95	3.26%	0.98	6.52%	0.79	-14.13%
11	1.27	1.39	9.45%	1.51	18.90%	1.76	38.58%
12	1.17	1.29	10.40%	1.41	20.80%	1.49	27.51%
13	1.14	1.27	11.40%	1.40	22.81%	1.47	28.95%
14	0.86	0.92	7.60%	0.99	15.20%	0.53	-37.78%
15	0.90	0.97	7.48%	1.04	14.96%	0.55	-39.06%
16	1.09	1.13	3.43%	1.17	6.86%	1.23	12.17%
17	1.26	1.39	10.01%	1.52	20.02%	1.47	16.54%
18	1.05	1.09	3.37%	1.13	6.73%	1.44	36.56%
19	1.24	1.36	9.28%	1.48	18.56%	1.95	56.69%
20	1.24	1.39	12.55%	1.55	25.10%	1.91	54.66%
21	0.87	0.90	3.26%	0.93	6.52%	0.70	-19.91%
22	1.21	1.33	10.24%	1.45	20.47%	1.75	45.05%
23	1.11	1.22	10.21%	1.33	20.42%	1.59	43.63%
24	1.08	1.19	10.19%	1.30	20.37%	1.35	25.00%
25	0.81	0.87	7.41%	0.93	14.81%	0.49	-39.51%
26	0.86	0.92	7.60%	0.99	15.20%	0.52	-39.18%
27	1.04	1.07	3.38%	1.11	6.76%	1.16	12.17%
28	1.30	1.42	9.23%	1.54	18.46%	1.90	46.15%
29	1.00	1.05	5.11%	1.10	10.21%	1.31	31.13%
30	1.18	1.30	10.26%	1.42	20.53%	1.87	58.61%
31	1.17	1.29	10.26%	1.41	20.51%	1.86	58.97%
32	0.73	0.77	5.48%	0.81	10.96%	0.45	-38.36%
33	1.14	1.24	8.49%	1.34	16.97%	1.60	39.98%
34	1.19	1.31	9.80%	1.43	19.60%	1.46	22.76%
35	1.16	1.29	10.82%	1.42	21.65%	1.36	16.84%
36	0.83	0.89	7.23%	0.95	14.46%	0.51	-38.55%
37	0.92	0.97	5.26%	1.02	10.53%	0.59	-35.79%
38	1.11	1.15	3.43%	1.19	6.86%	1.27	14.41%
39	1.29	1.41	9.29%	1.53	18.59%	1.93	49.60%
40	1.09	1.13	3.37%	1.16	6.73%	1.32	21.10%
41	1.27	1.39	9.28%	1.51	18.56%	1.97	55.03%
42	1.26	1.41	11.82%	1.56	23.63%	1.96	55.43%
43	0.89	0.93	4.21%	0.97	8.43%	0.67	-24.92%
44	1.23	1.33	7.96%	1.43	15.93%	1.65	33.94%
Ave	**1.10**	**1.19**	**7.78%**	**1.27**	**15.57%**	**1.33**	**21.22%**

The HCM methodology seems to over-estimate walking speeds by about 21%. Estimates during low LOS ranges were considerably higher than mid-range LOS thresholds whereas estimates during high LOS ranges are considerably under-estimated.

This is in line with the findings of the literature review in Chapter Two and the pilot study in Chapter Four, and also confirms the findings of the sensitivity tests presented in Section 6.5.8 in Chapter Six. The mean absolute error (MAE) is 0.39 and the mean absolute percentage error (MAPE) is 33.1%. Similarly, the mean square error (MSE) is 0.19, the route mean square error (RMSE) is 0.43, the Chi-square value is 6.06 and the Pearson correlation coefficient between the predicted and the observed speeds is 0.94.

The new Base Model produces considerably better estimates of walking speeds than the HCM methodology, with the overall difference falling to 7.8%. The mean absolute error (MAE) has significantly fallen to 0.09 and the mean absolute percentage error (MAPE) is now 7.0%. Note the original goodness-of-fit tests using the 20% holdout data produced a MAPE value of 8.7%, which is comparable. The mean square error (MSE) is now 0.01 and the root mean square error (RMSE) has significantly fallen to 0.09. The Chi-square value is considerably lower than the HCM methodology reducing to 0.30.

The new Group 1 Base Model also produces better estimates of walking speeds than the HCM methodology, but not as good as the full Base Model. This is to be expected, since the full Base Model includes more variables describing the effects of other factors on walking speeds. The overall difference is 15.6%, the mean absolute error (MAE) is 0.17 and the mean absolute percentage error (MAPE) is 13.0%. In addition, the mean square error (MSE) is 0.03, the route mean square error (RMSE) is 0.19 and the Chi-square value is 1.11. These are all considerably lower than the HCM methodology but not as low as the full Base Model, as one would expect.

The correlations were overall better for the new models compared to the HCM methodology.

7.5.2 Plots of Estimates against Observed Speeds

The estimates of pedestrian speed were plotted against the observed speeds to show how close they relate. The plot of the new full Base Model against the observed speeds is shown in Figure 7.1. The plot of the new Group 1 Base Model against the observed speeds is displayed in Figure 7.2. The plot of the HCM methodology against the observed speeds is displayed in Figure 7.3.

Figure 7.1: Plot of new full Base Model against Observed Speeds

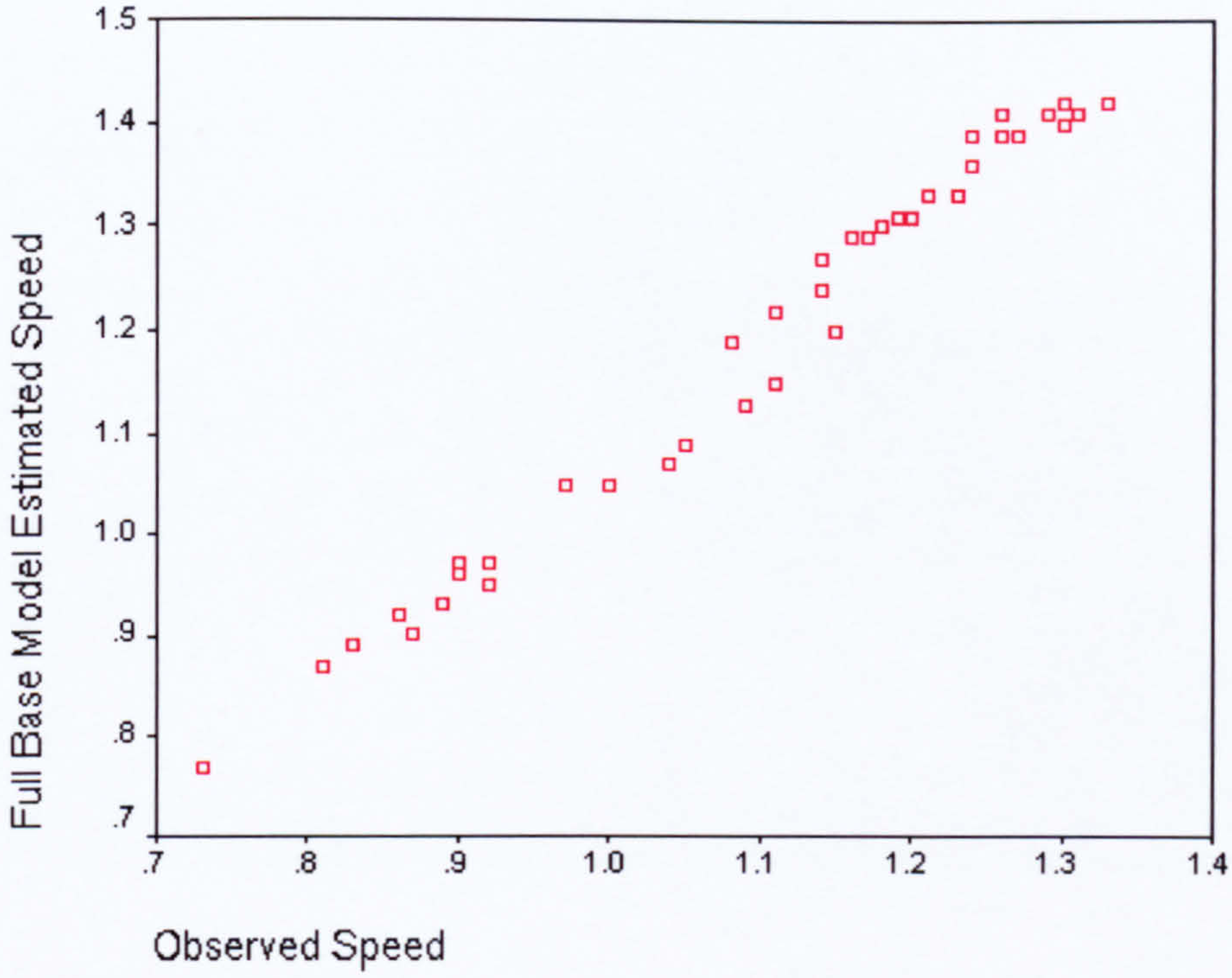


Figure 7.2: Plot of new Group 1 Base Model against Observed Speeds

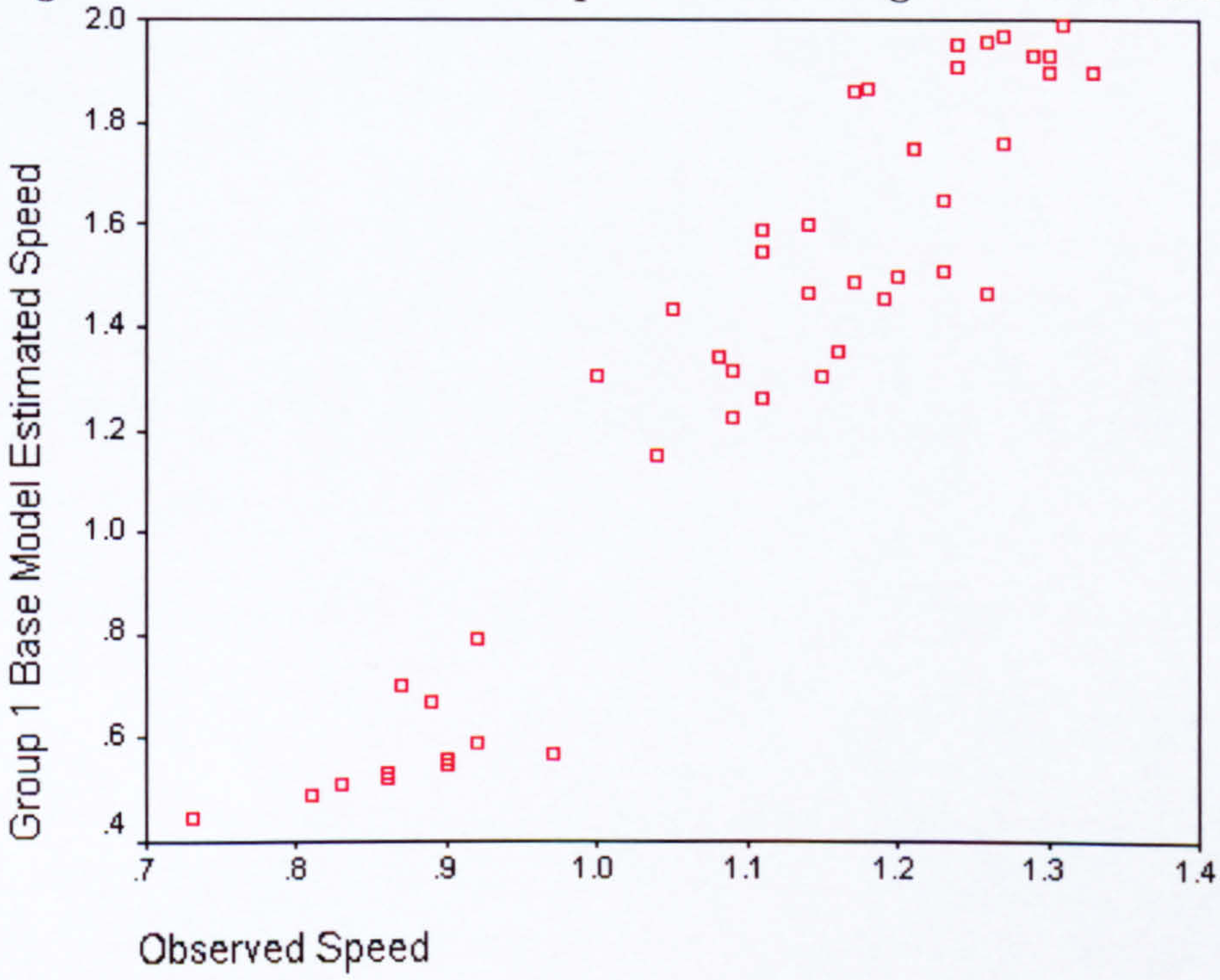
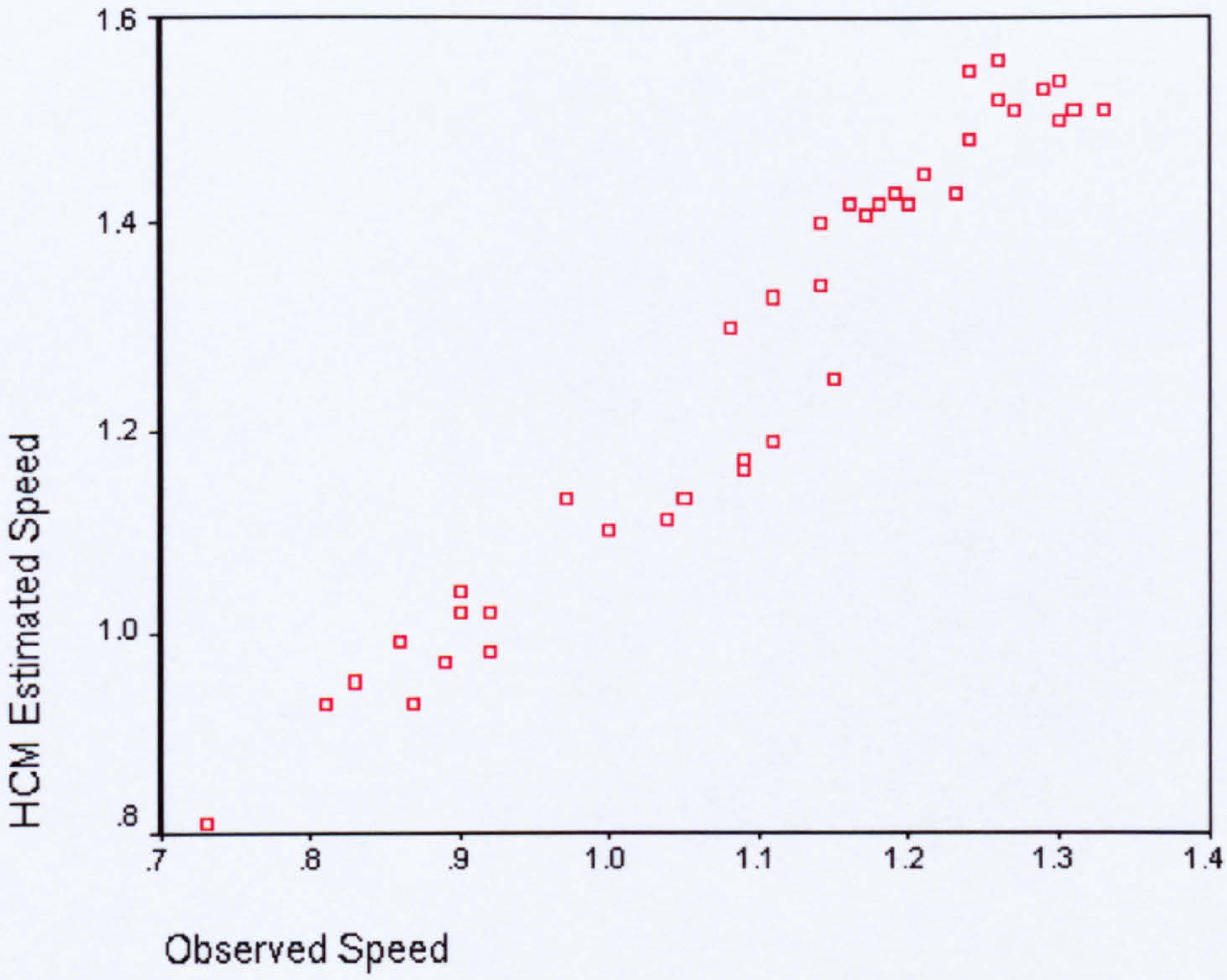


Figure 7.3: Plot of HCM Methodology against Observed Speeds



From the patterns displayed in Figures 7.1 to 7.3, it is clear that the quality of the predictions are poorer for the HCM methodology than the new models.

7.5.3 Paired T-Tests Analysis

A set of paired t-tests were carried out to assess the goodness-of-fit of the various models. This included paired t-tests of the new models and the HCM methodology against the observed data. The tests showed all the models were significant at the 95% level, but the new models gave better correlations (99% for the full Base Model and 97% for the Group 1 Base Model compared to 94% for the HCM methodology), and the mean differences between the estimates from the new models and the observed data were closer to zero than the differences between the estimates from the HCM methodology and the observed data.

7.5.4 Boxplots of Estimates against LOS

To show the estimates of walking speeds related to the different levels of LOS, a series of Boxplots of the percentage error against the LOS range were undertaken.

The plot of the percentage error against the LOS range of the new full Base Model is shown in Figure 7.4. The plot of the percentage error against the LOS range of the new Group 1 Base Model is displayed in Figure 7.5. The plot of the percentage error against the LOS range of the HCM methodology is displayed in Figure 7.6.

Figure 7.4: Boxplot of Percentage Error versus LOS of Full Base Model

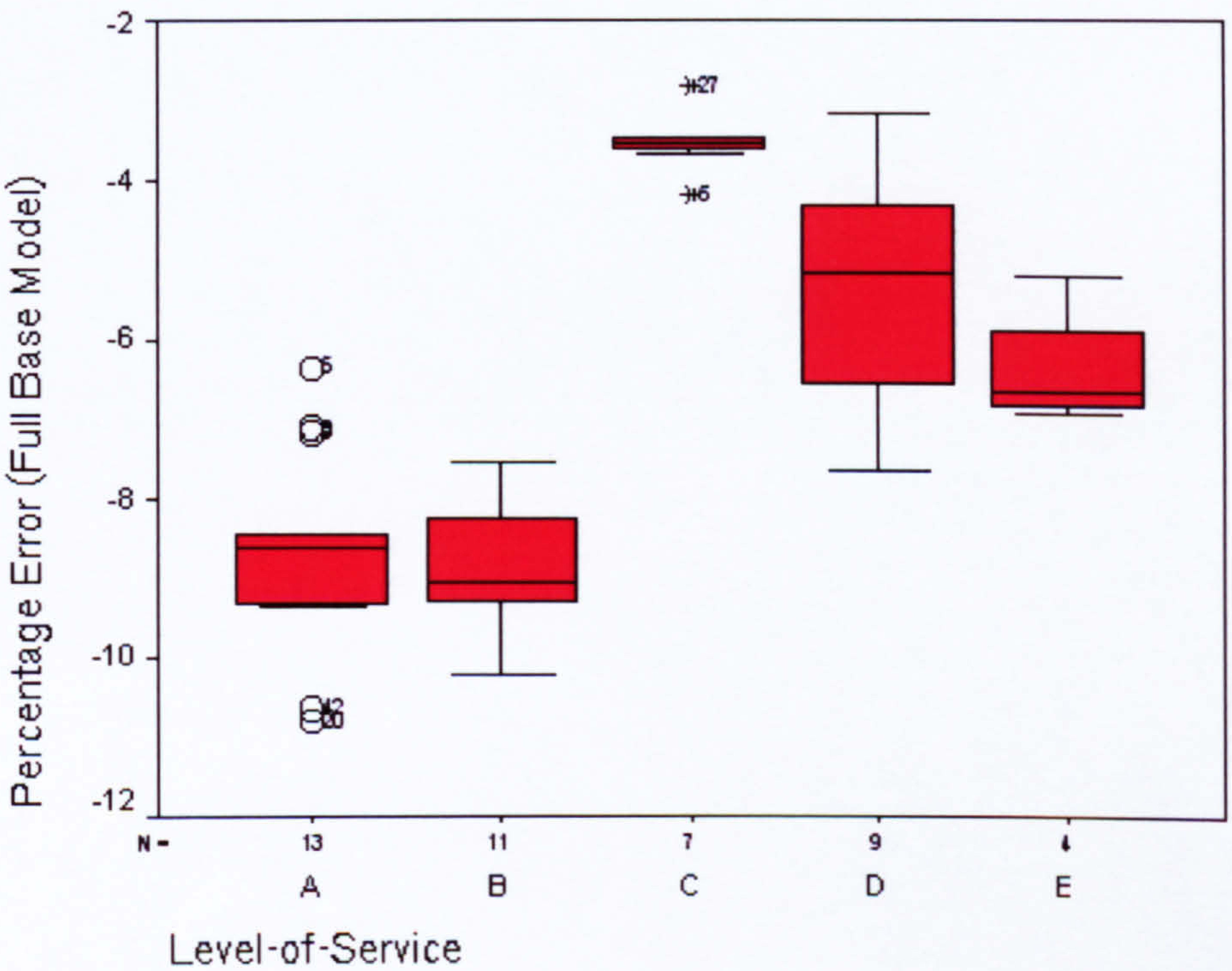


Figure 7.5: Boxplot of Percentage Error versus LOS of the Group 1 Base Model

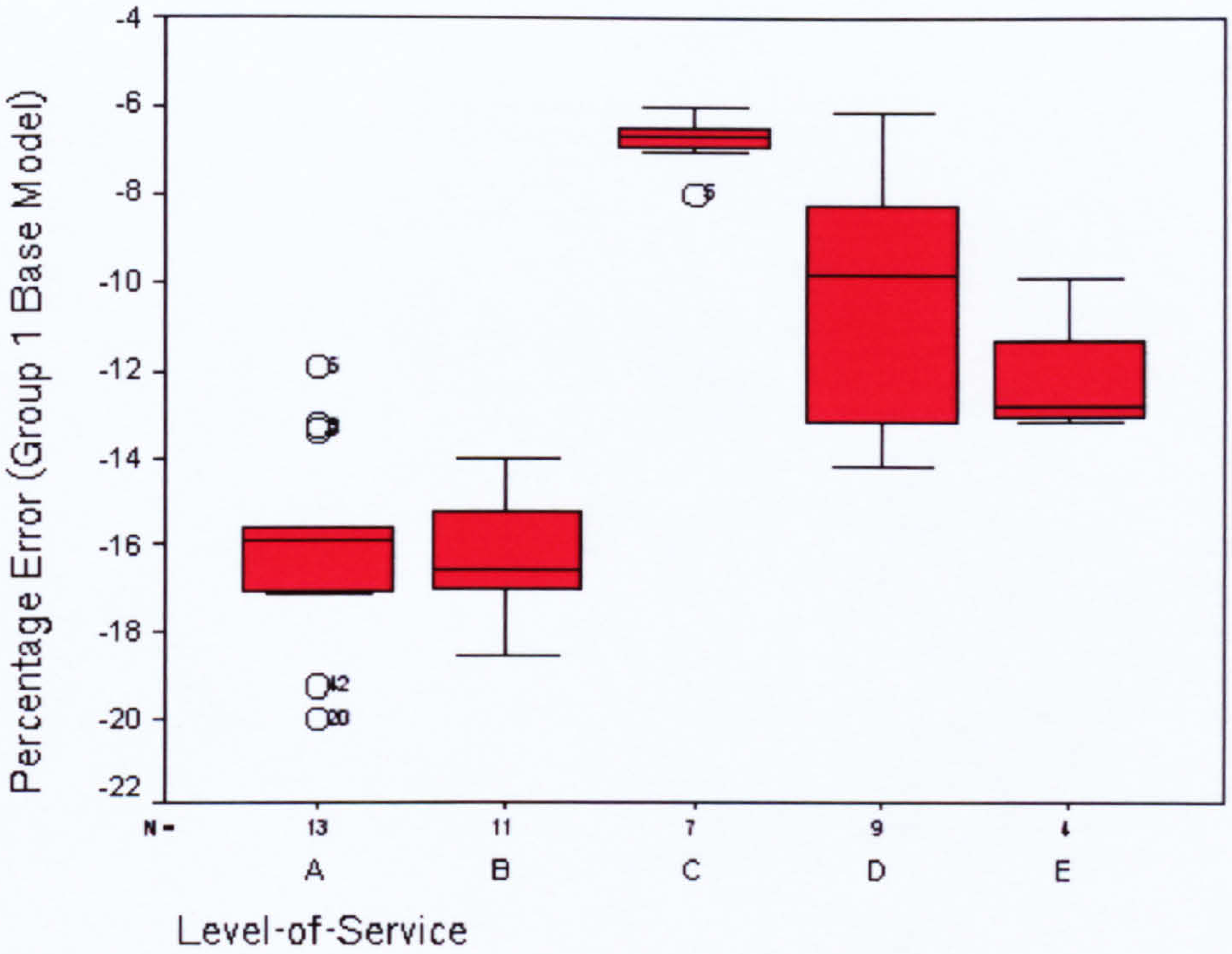
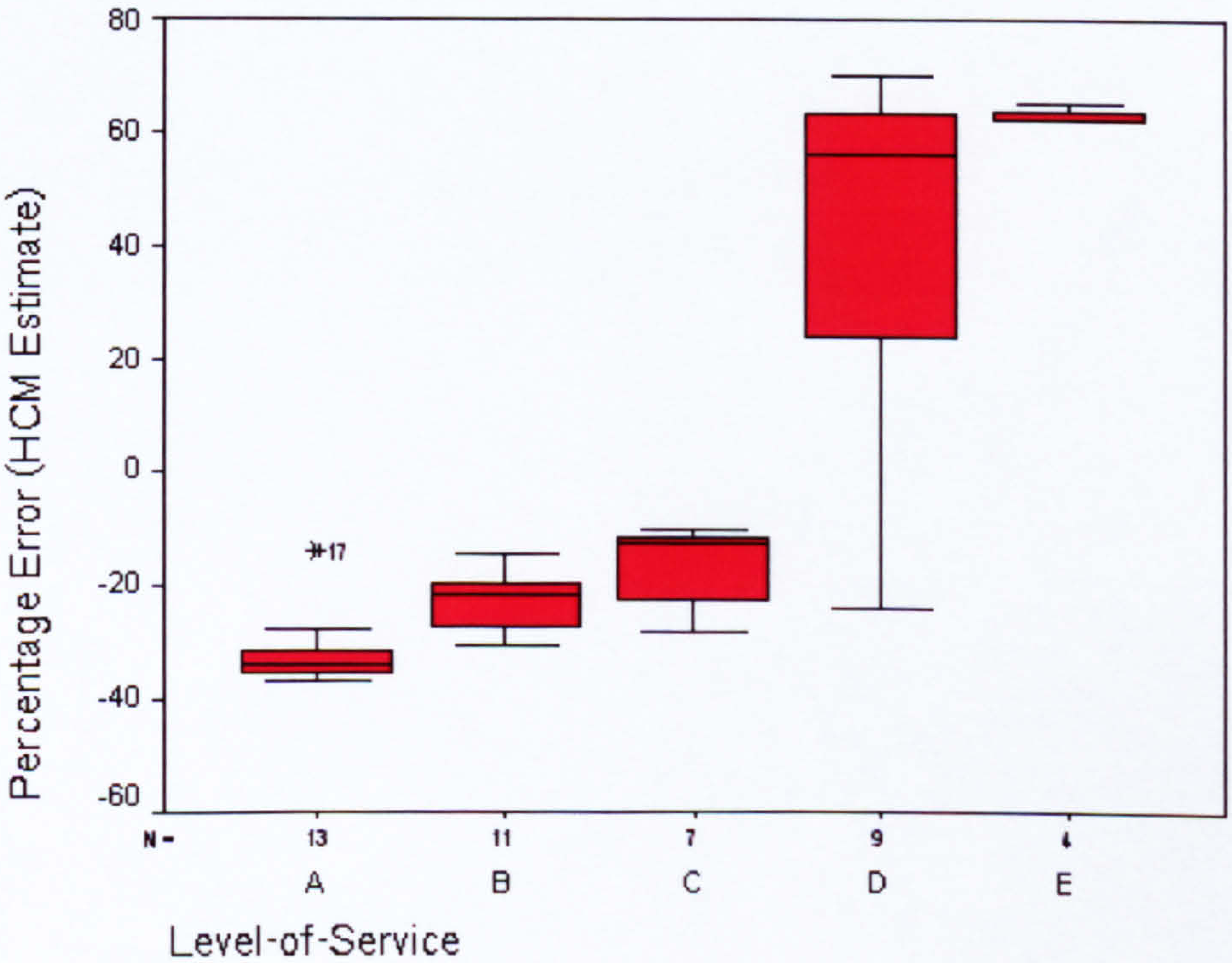


Figure 7.6: Boxplot of Percentage Error versus LOS of the HCM Methodology



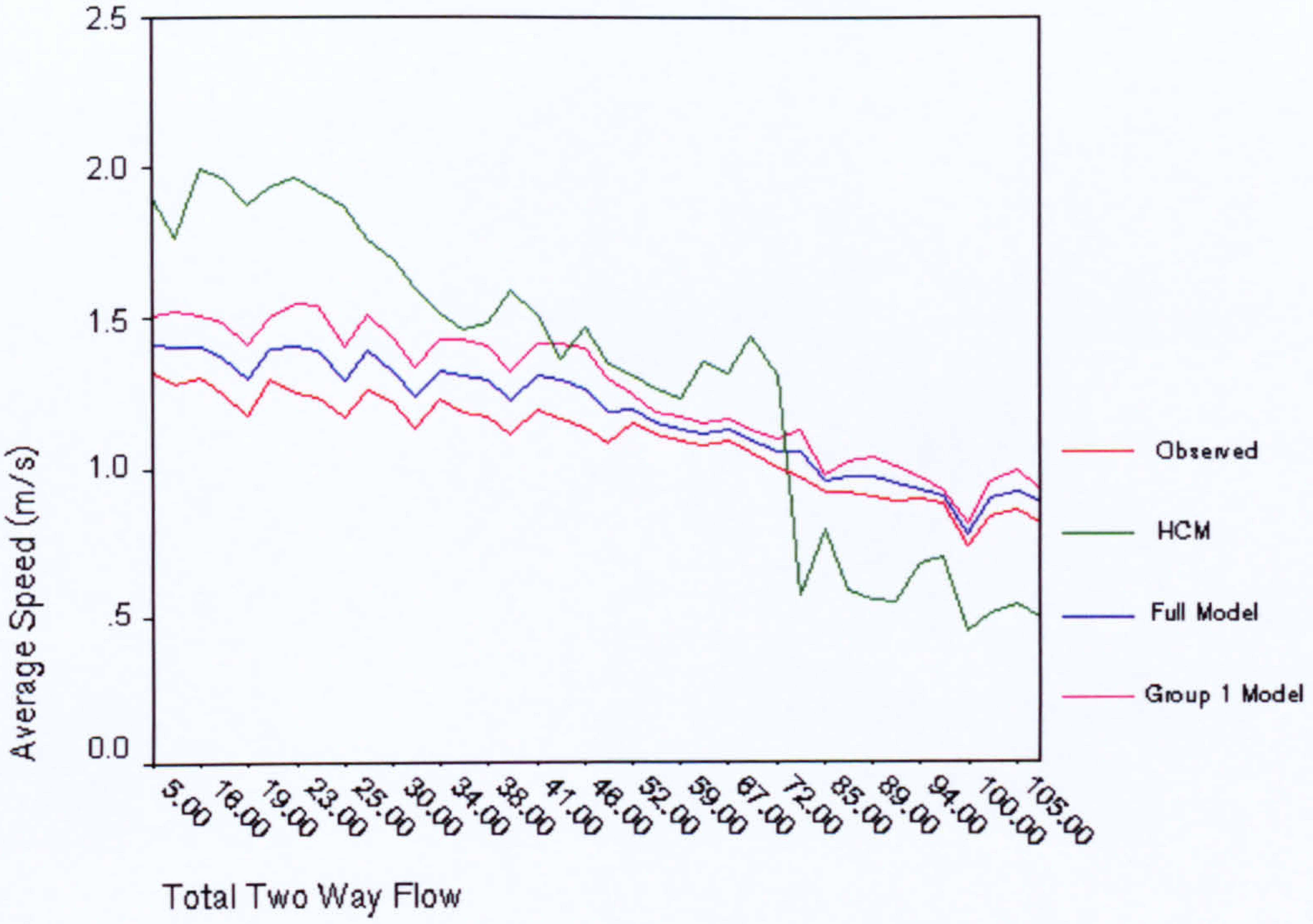
As can be seen from Figure 7.4, the new full Base Model shows a closer fit to the observations because the Y-Axis shows smaller differences than the equivalent values in the Group 1 Base Model (see Figure 7.5) and much smaller than those in the equivalent HCM methodology (see Figure 7.6), which shows very large variations than both new models.

It is interesting to note that the results in Figures 7.4 and 7.5 (obtained from the new models) are all negative and the results in Figure 7.6 (obtained from the HCM methodology) are a mixture, although mostly positive. It is also interesting to note that the results in Figures 7.4 and 7.5 are closer to zero than those shown in Figure 7.6, with the estimates from the full Base Model being the closest to zero.

7.5.5 Speed/Flow Relationships

Figure 7.7 shows the relationships between speeds and flows for the observed data, the estimates from the new Base Model, the estimates from the new Group 1 Base Model and the estimates from the HCM methodology.

Figures 7.7: Comparison of Speed/Flow Relationships from Model Estimates and Observed Data



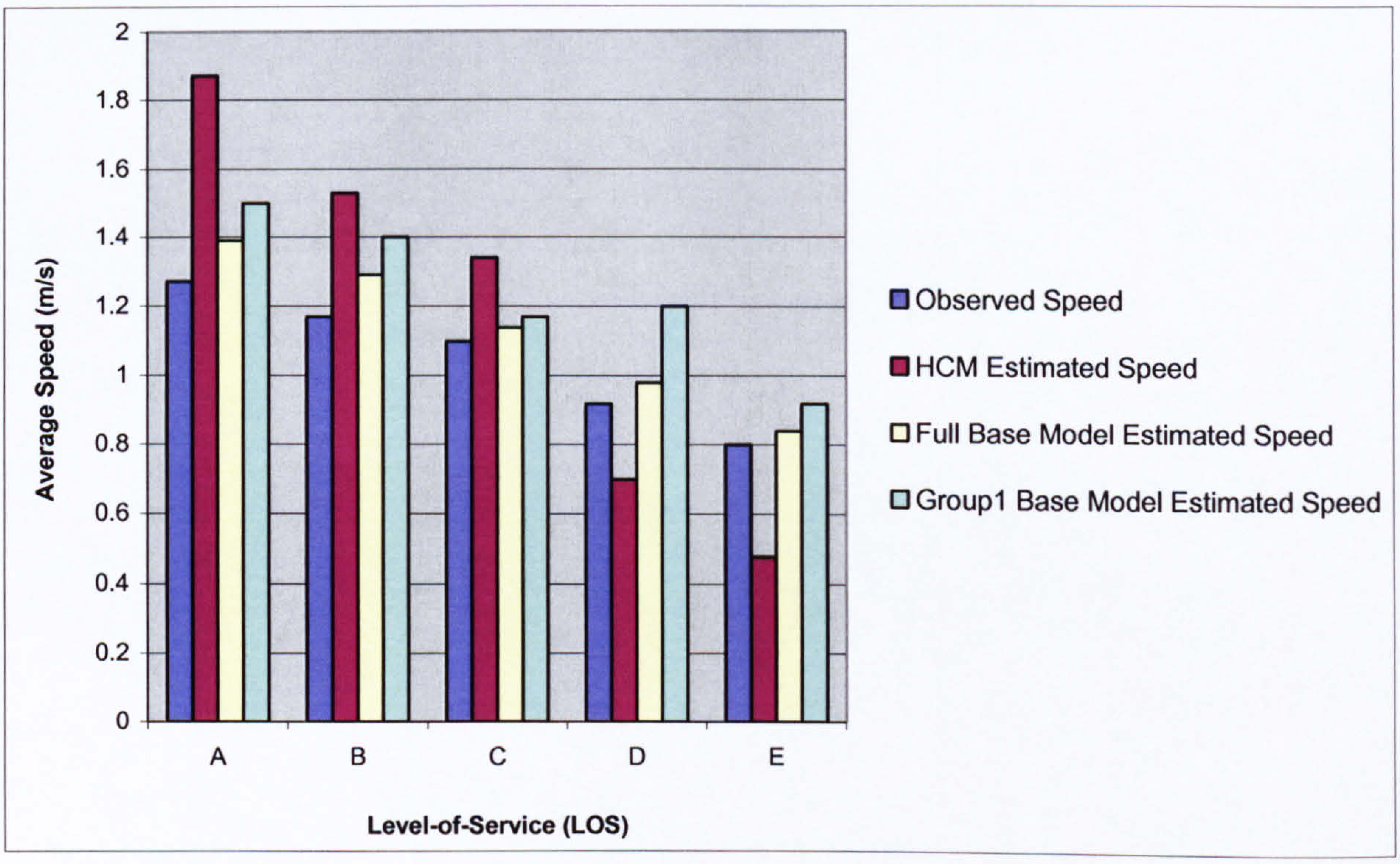
It is satisfying to see the curve of the new full Base Model is close to the observed data. This includes the closeness of the estimates to the observed values, the shape of the line and its slope. The new Group 1 Base Model also produces a similar shaped relationship, but it seems to be flatter than the observed data and its estimates look a little higher than the other new model. The slope of the line is also similar to the observed data. The HCM methodology produced a relationship which over-estimated speeds during low levels of flow and under-estimated speeds during high levels of flows. It is interesting to note this is similar to the findings from the pilot study presented in Chapter Four and the sensitivity tests presented in Section 6.5.8 in Chapter Six, and confirms the author's belief that the HCM methodology is not as accurate at high levels of pedestrian flows.

7.5.6 Speed/LOS Relationships

Another way of looking at the effects of flow is to compare speed against the LOS. This is examined in this Section.

Figure 7.8 shows the relationships between speeds and LOS for the observed data, the estimates from the new full Base Model, the estimates from the new Group 1 Base Model and the estimates from the HCM methodology.

Figure 7.8: Comparison of Speed/LOS Relationship from Model Estimates and Observed Data



It is gratifying to see the new full Base Model has a smooth looking fit to the observed data. The estimates of average speed are very similar to the speeds obtained from the observed data.

The estimates of average speed from the new Group 1 Base Model are similarly close, but look higher than the other new model. This is to be expected given the estimates are not as close, due to the fact the model does not have as much predictive power.

The HCM methodology produces a rather 'jagged' estimate, with much higher points during low LOS ranges and significantly lower points during high LOS ranges. Given the findings from previous statistical tests shown earlier, this is as one would expect.

7.6 Discussion

The results of the validation exercise are very encouraging, showing the new models developed in Chapter Six provide significantly improved estimates of walking speed.

It is interesting to note how close estimates from the new models are during both mid- and high-range LOS thresholds. During high LOS ranges Still (2000) suggests there are potential safety implications and Helbing (1995 and 1997) argues pedestrians are sensitive to changing their route choice to avoid excessive crowds. This implies the need for accurate analysis of walking conditions is most important during these LOS ranges and it is satisfying to see the new models perform well under these conditions, although the full Base Model performed better than the Group 1 Base Model. The literature review in Chapter Two showed there is a need for better models to undertake analysis during these conditions, which was also confirmed from the findings of the pilot study carried out and presented in Chapter Four. This, perhaps, is a reflection of the quantity of data collected over these LOS ranges.

Results from the statistical tests show the new models are significantly better than the HCM methodology. In particular, the mean absolute percentage error (MAPE) fell from over 33% in the HCM methodology to 7.0% in the new full Base Model. The MAPE of the full Base Model is close to the MAPE value of 8.7% obtained from the original goodness-of-fit tests using the 20% holdout data described in Chapter Six. This suggests this is not a one-off finding but rather a genuine indication of the model's potential.

The estimates of the Pearson correlation coefficient of the new models against the observed data gave an estimate of 0.99 for the full Base Model and 0.97 for the Group 1 Base Model, also showing a close fit.

Presented in Chapter Eight are conclusions based on the findings of this analysis and their implications for pedestrian modelling, and a discussion on recommendations for future research.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

This research examined the factors which influence walking speeds to provide a greater understanding of pedestrian movements and the characteristics of their needs. This was found to be important because current industry practices are based on principles and theories developed in the early 1970's and travel characteristics were believed to have changed significantly since then. This was confirmed by the review of travel patterns from the National Travel Survey which showed that walking is an important mode of travel but is often overlooked, highlighted falling trends for some trip purposes but high levels or indeed growth in walking for others, and discovered that Government transport policies are following a pro-active agenda to reverse the decline in walking trips by encouraging local authorities to pursue the enhancement of existing pedestrian facilities and the development of new infrastructure. It was therefore shown that there is a need for a more thorough understanding of the factors that influence walking speed, as this was one of the main variables used in the study of walking movements and the design of adequate pedestrian facilities.

A set of statistical relationships which improve the techniques of modelling pedestrian walking speeds were then developed and validated against a set of independent data. The predictive powers of the new models were compared against current methodology and found to provide significantly better estimates.

8.2 Aims of this Research

There were six main aims for this thesis, namely:

1. review current practices and procedures for modelling pedestrian movements;

2. identify the factors and variables used in current modelling processes and test their goodness-of-fit using independent data;

3. determine other factors which have a significant affect on the walking speeds of pedestrians in certain types of walking environments and conditions;

4. attempt to develop statistical relationships which can be used by transport planners to model the interactions between these factors and walking speeds, and thereby assist with the study and design of pedestrian facilities;

5. test and validate the statistical relationships developed; and

6. identify and discuss future areas of research.

The intention was to provide a greater understanding of the dynamics affecting walking speeds, thereby assisting transport planners and engineers with the study and design of suitable pedestrian facilities.

8.3 Research Findings

8.3.1 Overview

The main findings of this research can be summarised as follows:

- the Highway Capacity Manual (HCM) methodology is the main procedure used for modelling walking speeds. However, tests undertaken on the HCM methodology showed that it describes just over half of the variations of the factors that influence walking speeds and there are many more variables which effect pedestrian speeds (not just flow and space as used in the HCM methodology). These additional variables were found to belong to three groups of classifications, most of which are within the design control of the transport planner and engineer or are readily available;

- speed has been found to be one of the primary Measures of Effectiveness (MOE) in the current HCM uses speed (Chapter 11; TRB, 2000), by many transport planners in the UK and other parts of Europe (Zegeer et al, 1994) and in various leading industry pedestrian simulation software models;

- the analysis in this thesis replicated the HCM methodology and added additional geometric variables, which are not currently used by the HCM but can readily be measured or are within the control of the pedestrian planner, into the basic HCM relationship based on the findings of the literature review. It was shown that adding these additional geometric variables significantly improves the prediction of walking speeds, compared to the basic HCM methodology, and also explains more of the variations that influence walking speeds;

- further variables which are not directly within the control of the transport engineer were also tested. Even though these variables are not used by the HCM, the results showed further improvements in the estimation of walking speeds compared to the basic HCM methodology and also further explanations of the variations influencing speed;

- this corroborated the Research Hypotheses underpinning this thesis and showed a lack of understanding of all the complexities of walking characteristics and the extent to which variations occur both within and between different walking conditions;

- the HCM methodology as it currently stands is not fully applicable to the types of walking environments that are the subject of this research (on-street walkways in UK shopping areas and Central Business Districts);

- a set of new statistical models were developed which encompass more variables than are currently used by the HCM methodology. These new models have better predictive powers than the HCM methodology, and have been categorised into two groups: Geometric-only Models and Full Models. The Geometric-only Models contain only those variables which are directly within the control of the transport engineer. The Full Models include geometric, environmental and land-uses variables;

- the new models were validated against an independent set of data which showed that the new models produce significantly better estimates of walking speeds than the HCM methodology; and

- the statistical tests on the comparisons of the two groups of new models developed, Geometric-only Models against the Full Models, has shown that the Full Models explain up to 87% of the variations in speed and the Geometric-only Models explain up to 80% of the variations, suggesting the land-use factors are not as influential as the geometric factors. This confirms the theories set out in Sections 5.4.3.3 and 5.4.3.5 in Chapter Five that pedestrian walking speeds are influenced by some variables that are not directly within the control of the transport planner, but it also shows that this level of influence is not much more than the effects of the enhanced geometric models featuring more variables than the basic HCM methodology all of which are controllable by the designer.

8.3.2 Summary of the Effects of Variables on Speed

The expected effects of the new variables on speed have been examined against the actual results obtained from the final best-fit model. Out of 26 variables, 13 were found to be statistically significant. However, this does not mean the other variables do not significantly affect speed. On their own, the statistical tests presented in Section 6.4 of Chapter Six showed they do indeed significantly influence speed but the model development found many to be highly correlated together or with other variables in the best-fit model and so there was no requirement to include them all together. Table 8.1 shows the expected effects of the new variables on speed against the actual results obtained from the final best-fit model. Clearly, where a variable was not included in the best-fit model, no measure of its scale of impact on walking speed could be made. Therefore, Table 8.1 also shows which variables were not used in the best-fit model.

Table 8.1: Results of the Effects on Walking Speeds of the Variables (tests applied to reciprocal of pedestrian speed)

Group	Variable	Significant	Expected Effect on Speed	Actual Effect on Speed
HCM	Den_Centre	Yes	Large Negative	Large Negative
	Flow	Yes	Large Negative	Large Negative
Additional Geometric Variables	Gradient	Yes	Large Negative	Small Negative
	Guard_Rail	Yes	Slight Negative	Not Used in Model
	Furniture	Yes	Slight Negative	Not Used in Model
	Entrance_Exit	Yes	Slight Negative	Not Used in Model
	Junction	Yes	Large Negative	Large Negative
	Bus_Stop	Yes	Negative	Small Negative
	Bus_Lane	Yes	Negative	Not Used in Model
Pedestrian Characteristics	Gender	No	Positive	Not Used in Model
	Age	Yes	Large Negative	Large Negative
	Infirm	Yes	Large Negative	Not Used in Model
	Bags	Yes	Negative	Negative
	Stops	Yes	Negative	Not Used in Model
	Child_Animal	Yes	Negative	Not Used in Model
	Group	Yes	Negative	Not Used in Model
	Deviate	Yes	Negative	Not Used in Model
Adjacent Land-Uses	Retail	Yes	Negative	Negative
	Houses	Yes	Positive	Not Used in Model
	Offices	Yes	Large Positive	Large Positive
	Vehicles	Yes	Negative	Not Used in Model
	Parking	Yes	Negative	Not Used in Model
Environment and Time	Winter	Yes	Positive	Positive
	Rain	Yes	Small Positive	Small Positive
	Weekday	Yes	Large Positive	Not Used in Model
	Peak	Yes	Large Positive	Large Positive

As can be seen from Table 8.1, most of the expected effects on walking speeds matched the actual impacts obtained. The exceptions, however, were follows:

- gradient was much smaller than originally expected;
- the presence of a bus lane was also smaller than originally thought; and
- shopping area was larger than originally believed.

The reasons for the effects of gradient and the presence of a bus lane being smaller than expected could be due to the low sample sizes of data with these features. Similarly the strong performance of the shopping area variable could be due to a high sample bias, as most of the sites selected were shopping environments.

8.4 Hypothesis Testing

8.4.1 Testing LOS Ranges

A series of Research Hypotheses were developed to test some of the propositions identified in the literature review and the aims of the research, following an initial pilot study. Two hypotheses were identified with the aim of producing a better understanding of the impacts of denser LOS ranges. They were:

> *Hypothesis One:* *Average walking speeds in denser LOS ranges (e.g. E and F) for on-street shopping areas will be lower than the average values documented in the HCM planning guidelines.*

> *Hypothesis Two:* *Some of the average walking speed results for the low and medium LOS ranges (e.g. A to D) identified by this research will be reasonably close to those produced from past work using similar LOS data and analysis techniques, and incorporated in the HCM.*

The findings of the model validation showed that under low and medium LOS ranges (LOS ranges A to D) the HCM methodology consistently under-estimated the walking speeds from the independently observed data. The exceptions were LOS ranges E and F, where the HCM methodology consistently over-estimated speeds. This has shown the degree of variation from the current industry-standard averages. This is logical since the literature review also showed that the relationships in the HCM methodology were not based on data from denser LOS ranges (e.g. E and F). It is considered this proves average walking speeds in denser LOS ranges for on-street shopping areas are lower than the average values documented in the HCM planning guidelines for these LOS ranges.

The second hypothesis is intended as a check of the findings of this study. Again, the findings of the model validation showed that the estimates in walking speeds from the HCM methodology were closer to the independent data during low and medium LOS ranges (e.g. A to D) then higher LOS ranges (e.g. E or F). This seems to corroborate the theory that the HCM methodology would perform better during low and medium LOS ranges (e.g. A to D). In addition, the new models developed also performed well at these LOS ranges. It is therefore considered that the new models have been validated and the second hypothesis is valid.

8.4.2 Identify which Pedestrian Characteristics and Environmental Factors have a Significant Influence on Walking Speeds

Four hypotheses were identified, which were intended to identify some of the specific pedestrian characteristics and environmental features which have a significant impact on walking speeds, but are not currently used in pedestrian modelling:

> *Hypothesis Three:* *Some of the different characteristics of a pedestrian (e.g. age, gender, whether they are carrying baggage) will significantly slow walking speed.*
>
> *Hypothesis Four:* *Walking in groups of two or more pedestrians will significantly slow walking speed.*
>
> *Hypothesis Five:* *Walking speeds are significantly slowed by certain physical geometric layout factors (e.g. walkway gradient, width, proximity of road junctions).*
>
> *Hypothesis Six:* *Pedestrian walking speeds are significantly different at different time periods of the day.*

The effects of different variables on pedestrian speed was investigated and a number of variables, which are not currently used in pedestrian modelling studies, were identified as having significant effects on walking speeds.

The analysis showed that different characteristics of a pedestrian, walking with other pedestrians, certain physical geometric layout factors and different times of the day significantly effect pedestrian walking speeds.

It is therefore considered that this confirms the hypotheses that there are many variables which influence the walking speeds of pedestrians and that the current practice of only using pedestrian flows or densities might not be sufficient to capture all the relevant factors influencing walking speeds. This is especially important since many of the identified factors are within the designer's control.

8.4.3 Assessing the Effects of Different Pedestrian Environments on Walking Speeds

The last hypothesis was intended to help identify how various pedestrian walking environments (and their associated characteristics) affect pedestrian walking speeds:

> *Hypothesis Seven:* *Pedestrian speeds are significantly different in different walking environments (e.g. walkways next to office buildings, retail shops) and weather conditions (e.g. rain, winter).*

The investigations have shown that location and environment (both built and natural) do significantly affect walking speeds.

8.5 Discussion

8.5.1 Consequences and Benefits of this Research

The findings of this research suggest there is considerable scope for improvements of the HCM methodology, thereby improving the study of pedestrian requirements and the design of new facilities.

The HCM methodology is particularly weak in estimating walking speeds during high-range LOS thresholds, where the need for accurate analysis of walking conditions is arguably most important due to potential safety implications (Still, 2000) or sensitivities to changing their route choice to avoid excessive crowds (Helbing, 1995 and 1997).

The literature review and the initial analysis (pilot study) in this thesis have shown that the HCM methodology only accounts for just over half the factors which influence walking speeds, and there is a need for more accuracy. The HCM methodology as it currently stands is arguably not suitable for studying surface on-street walkways in UK shopping areas and Central Business Districts, and care is needed if it is being used in these types of environments. This does not mean that the methodology is technically wrong, but that its uses are limited.

On a more positive note, however, there is now a major opportunity to significantly improve the quality of the analysis of these types of walking environments, thereby assisting in designing improved infrastructure to meet the varied needs of pedestrians. The detailed, comprehensive, research undertaken in this thesis has produced a set of new models which have been shown to significantly enhance estimates of walking speeds while also including a number of variables which are easily within the control of the transport designer.

The accuracy of these new models has been strongly demonstrated in both the initial model validation and a fuller, more comprehensive, model validation exercise using independent data. The new models were found to perform very well across all the LOS ranges.

The data required for the new models is not unreasonable and is readily available, and allows for considering the effects of different mixes of conditions, type of walking environments and characteristics of pedestrians. This will help provide a more holistic understanding of the factors affecting walking and provide transport engineers with a deeper insight when designing new pedestrian facilities or improving existing infrastructure. In particular, transport planners can use the new models to identify the needs of specific types of pedestrians. An example could be those with mobility constraints; this is more than just the infirmed and includes the elderly, people carrying bags or luggage, and those accompanied by small children. All these groups of people have been identified by the Scottish Executive in its Scottish Transport Appraisal Guidance (Scottish Executive, 2001) as having specific accessibility issues which can hinder their walking. The factors affecting these vulnerable members of society, among others, are included in the new models developed in this thesis. An explanation of how the new models could be used in real-life applications and new situations is set out in Section 8.6 in this Chapter.

It is acknowledged, however, that the HCM methodology allows for more disaggregated models of walking speeds for various subgroups within the pedestrian flow to be developed. Similar disaggregated modelling could also have been undertaken in this thesis, however this would not have allowed for the examination of the key variables being investigated in this thesis. Therefore, it was felt more valuable to focus on the core objectives of this study. In addition, this also allowed the author to identify a set of pragmatic models for use in pedestrian studies with a manageable level of data requirements.

However, future research could examine the potential for developing disaggregated sub-models. In order to determine the effects of variables which were found to influence walking speeds on their own but were excluded in the Full Base Models and the Group 1 Base Models because they were correlated with other variables (e.g. Infirm or Child_Animal), separate sub-models would have to be constructed.

8.5.2 Data Needs of the Variables

The process used to collect data for this thesis was based on potential modelling variables both within and out with the control of the designer or planner. Many of these had already been identified in the literature Review. Only 13 variables were finally used in the best-fit model developed. These variables can be seen in Table 8.1 and relate to the Full Base Model.

This suggests there is only a need to collect data on these variables, if the Full Base Model is to be used. In particular, the age variable does not need to be disaggregated into the 4 categories suggested by the literature review.

8.5.3 The Use of Speed as the primary Measure of Effectiveness

The current HCM uses pedestrian space as the primary measure of effectiveness (MOE), with mean speed and flow rates as secondary measures (Table 2; TRB, 2000). In particular, the HCM's arterial analysis chapter (Chapter 11; TRB, 2000) uses overall average travel speed as the MOE. Furthermore, the review of industry practices in the UK and other parts of Europe by Zegeer et al (1994) has shown that speed is predominantly used as a MOE, and also as a means of testing the effectiveness of enhancements to existing walking facilities or comparing different designs of new infrastructure. In addition, the literature review also showed that speed is one of the main parameters used by pedestrian modelling software programs like PEDROUTE, LEGION and other leading industry models (see Section 2.3.2 of Chapter Two).

Given the findings of this thesis have shown there are a wide number of factors potentially influencing pedestrians, this raises the question about the appropriateness of using speed on its own as a suitable MOE.

8.5.4 General Purpose Models

The new models developed in this thesis are based on extensive data collected at different sites across the country. While these sites include shopping streets (both pedestrianised and non-pedestrianised), central business districts (office locations) and residential areas, the majority of the data collected from these sites was from shopping environments. However, it is the author's view that the new models are not retail models and can be used for general purpose pedestrian modelling, as the data includes significant proportions of data collected from non-shopping areas.

Moreover, the variables incorporated in the models include parameters that represent the geometric layout of the walkway, which the literature review has shown to be influential across many types of walking environments and travelling conditions. Furthermore the statistical tests on the comparisons of the two groups of new models developed, Geometric-only Model against the Full Model (which includes geometric, environmental and land-uses variables), has shown that the Full Model explains 87% of the variations in speed and the Geometric-only Model explains 80% of the variations, suggesting the land-use factors are not as influential as the geometric factors.

8.5.5 Research Findings in the context of Planning Guidelines

The literature review showed that some transport planning organisations have published their own set of guidelines explaining how they believe pedestrian facilities should be studied or designed (e.g. Institute of Transportation Engineers, 1976; and London Underground Limited, 1990, 1993 and 1997). Controversially, the Institution of Highways and Transportation (IHT, 2000) have advised not to model pedestrian movements. In their Guidelines for Providing for Journeys on Foot they say (Page 48, Paragraph 3.29) they say:

> *"The absence of specific pedestrian models for planning new developments is not necessarily a major problem. Most pedestrian networks are planned without models. Observation and experience are probably more important. It is also worth remembering that models can be expensive to construct and are not always sufficiently accurate."* (IHT, 2000)

The author would agree with the statement that most pedestrian networks are planned without models, based on this research and also his experience working for various Local Authorities and Transport Consultants in the UK. However, this is arguably not a suitable justification for not using more scientific planning tools, especially if they are readily available and easy to apply as the new models developed in this thesis. In addition, the above advice seems to be rather subjective, and there is no data or evidence presented in the IHT Guidelines that justifies the statement that observation and experience are more important.

Furthermore, the author believes part of the reasons for not using pedestrian models is that suitable models are not readily available. This was one of the aims of this research, which has successfully developed a set of models which are easy to use and whose data requirements are fairly inexpensive and not much more than the basic HCM methodology.

As far as accuracy is concerned, the accuracy of the new models in this thesis has been strongly demonstrated in both the initial model validation and a fuller, more comprehensive, model validation exercise using independent data. The new models were found to perform very well across all the LOS ranges.

It is the author's view that there is a role for modelling pedestrians, which can provide more insight for the study process and design because the model allows the transport planner to examine a much wider range of issues and scenarios than could otherwise be tested. Modelling also helps to quantify the potential scale and magnitude of any benefits obtained by a proposal, and also allows comparing one design option against others to identify the best solution.

8.5.6 New Models in relation to the Literature Review

The analysis in Chapter Six and the new models developed confirmed the findings of the literature review and showed there are many more variables which effect pedestrian speeds (not just flow and space as used in the HCM methodology). These additional variables were found to belong to three groups of classifications, most of which are within the design control of the transport planner and engineer or are readily available.

However, the literature review suggested there were 26 variables (in addition to flow and density) which should be used in the analysis, but the new models developed only require 13 variables. This does not mean the other variables do not significantly affect speed. On their own, the statistical tests presented in Section 6.4 of Chapter Six showed they do indeed significantly influence speed but the model development found many to be highly correlated together or with other variables in the best-fit model and so there was no requirement to include them all together.

More surprisingly, perhaps, was the discovery that two variables (gradient and the presence of a bus lane) have a smaller impact on walking speed than originally expected, while the variable on shopping area was larger than originally believed. Potential reasons for these effects being different to expectations are discussed in Section 8.3.2.

8.5.7 Potential Limitations of the New Models

The limitations of the new models include observational weaknesses when collecting some of the data they require. While most of the data can be measured (e.g. flow, walkway width) others are subjective. As mentioned in Section 5.4.5 in Chapter Five, age was obtained by visual inspection of the pedestrian and as such different people have different opinions as to which banding to classify the same pedestrian.

Another point to note relates to the variables examined and sites selected to collect data. While the justification for the data collected was based on the literature review and the initial analysis (pilot study), some variables in the data sets might produce positive variations under the survey conditions and sites used in this thesis but negative results in another. For example, gender was not found to be significant in the sites surveyed in this thesis, but other researchers found gender to be statistically significant in influencing walking speeds (e.g. White, 1994). In some contexts, gender could be much more significant than the models developed in this research suggest. For example, mothers with toddlers or mothers with older children could have to walk at a slower speed in order to travel with their accompanying child.

A final issue worth remembering is the range of some of the variables used in the new models are limited to the narrow scales of variations. For example, the range of data collected for the gradient variable was more limited than other variables.

Although it is the authors view the data used in this thesis is very comprehensive and covers most travel conditions (including all LOS ranges), the new predictive models developed in this study have known ranges and characteristics. In particular, some of the key variables might only produce suitable estimates within the ranges of the relevant data. The suitable ranges of the key variables of the new models are shown in Table 6.16.

8.6 Recommendations for using the New Models

8.6.1 Where the New Models fit into the Study and/or Design Process

Pedestrian models are developed to assist transport planners and engineers with the design of suitable pedestrian facilities or enhancement of existing infrastructure. For example, they can identify the required width of a walkway or pedestrian space for a required LOS.

The basic method used by the engineer or designer is the HCM methodology (TRB, 2000). While the HCM is a North American guidance, it is also widely used in the UK and throughout Europe (Zegeer et al, 1994) and has been incorporated into various computer-based software modelling programs like PEDROUTE, LEGION and other leading industry software applications (see Section 2.3.2 of Chapter Two).

However, there are a number of limitations with the basic HCM methodology, which have been raised by various studies and researchers (e.g. Still, 2000; and Lam and Cheung, 2000). This is because the HCM methodology primarily uses flow and pedestrian density as the factors in its analysis process.

Some of these limitations have been overcome by the various computer-based software modelling programs, but they have to be applied for specific environments or walking conditions. Furthermore, these models still only include a limited number of potential variables which explain the interactions of pedestrians either with other pedestrians or their surrounding conditions. Some have developed expanded models which include more variables trying to explain the factors that influence walking (e.g. Helbing, 1995 and 1997; and Daamen, and Hoogendoorn, 2003a) but this thesis has shown there are many more variables which could potentially influence walking.

This thesis has developed a new set of models which can be used to study a wide range of walking situations and include a rich list of variables representing the effects of different geometric parameters (much more than the basic HCM methodology), land-uses, pedestrian characteristics, travelling conditions and walking environments (both built and natural). This will allow the designer to examine the effects of all these issues separately and also in combination, giving a greater insight into the study and design process. This is especially the case since most of the variables have been found to be within the direct control of the transport planner and designer.

All the variables in the new models have been shown to be statistically significant and they have been categorised into two groups, based on variables which solely use geometric parameters and therefore are under the influence of the pedestrian planner or variables which include geometric factors plus other variables which are not easily under the control of the engineer but nonetheless can be observed or estimated from other sources.

To make them easier to understand, the new models presented in this research have been grouped into the following hierarchy (rising in levels of accuracy as their data requirements increase):

- Geometric-based Models – these use only those variables directly within the control of the transport planner or designer (see Section 6.5.6.2), and consist of two forms:
    1. Basic Model – this is based on geometric-only information to represent the characteristics of the walking environment and uses density alone as a measure of pedestrian demand, without any data on flows. This is suitable for use in studies were data on pedestrians flows is not available. An example of when this model could be used is the study which looked at extending sections of the walkway in Oxford Street, London (City of Westminster Council, 1996). The HCM methodology was used to examine the geometric layout of the existing walkway with a view to identifying whether the capacity required increasing and what optimum width would be needed to meet the expected pedestrian flows. Using the HCM methodology the planners considered the effects of density, which is derived using the geometric parameters of width and length. However, this new Group 1 Base Model would have allowed the planners to consider the effects of other site parameters such as gradient, the proximity of junctions and the presence of vehicles. All of these other variables have been found to significantly affect pedestrian movements in the literature review, and therefore the model

would have provided a deeper insight into the optimum width of the planned walkway improvements as well as more accurate estimates; and

2. Basic Model with the Ratio of Flows – this is the same as the above model but incorporates the ratio of the directional pedestrian flows. This would require some form of survey or estimates of flows. Estimates from this model are better than those from the previous model. The previous real-life example of a study at Oxford Street could also have benefited from this model. With the added data on pedestrian flows, the accuracy of the modelling would have been improved for little costs to the data collection.

- Full Models – these require data for all the variables identified (see Sections 6.5.5.1 and 6.5.5.2), and also fall into two types:
    1. Full Model – this uses only density as a proxy for the effects of flows. This does not require estimates of pedestrian flows or surveys of observed movements, but does require more details of the walking environment being studied and the characteristics of the pedestrians using the area. An example of when this model could be used is the study which looked at on-street access improvements to walkways around Bearsden Rail Station, West Dunbartonshire (Scott Wilson Scotland Ltd, 2002). Modelling was undertaken using the HCM methodology but this could not estimate the effects of elderly pedestrians, people carrying bags

(e.g. shoppers) or luggage as would be expected leaving a railway station, the effects of adjacent bus stops, the geographical effects of nearby offices or retail land-uses, and travelling at different times of the day (e.g. peak times) or seasons (e.g. winter). Furthermore, the features and benefits of different improvement designs was measured using accessibility indices based on walking speeds, to help identify which designs gave the best value-for-money. This is a requirement set out in the Scottish Transport Appraisal Guidance (Scottish Executive, 2001) which the Government requires Transport Authorities to follow when examining similar transport improvements. Unfortunately, the HCM methodology does not include these variables and the planners found that the accuracy of the estimates produced from the HCM methodology had to be compensated by the fieldwork. Consequently, the planners had to supplement their analysis with extensive site surveys and pedestrian observations. This significantly increased the study time and associated costs. However, the new Full Base Model includes all the variables the required and others, and would have allowed the examination of these factors without the need for costly fieldwork in addition to providing more accurate estimates than obtained from the HCM methodology; and

2. Full Model with the Ratio of Flows – this is the same as the Full Model but requires pedestrian flow data by direction of travel. Estimates from this model are better than those from the Full

Model. The previous real-life example of a study at on-street accesses to Bearsden Rail Station could also have benefited from this model. The additional information on pedestrian flows would have further improved the accuracy of the estimates of accessibility indices (which were based on speeds), since the new model describes almost double the variations in speeds than the HCM methodology.

8.6.1.1 Relation to the Design Process

The new models developed in this thesis have shown marked improvements in the accuracy of estimating walking speed compared to the HCM methodology. The trade-off between the accuracy and costs of using the new models are discussed in Section 8.6.2 later in this Chapter. However, it is useful to also relate the improved levels of accuracy gained from the new models to the actual design process.

Although the new models are more precise in estimating walking speeds than the HCM methodology, some might question the need for this improved accuracy given the fact that the HCM methodology has some quite wide ranges defining the different LOS ranges. These ranges can be seen in Table 2.2 in Chapter Two of this thesis, which shows the LOS criteria from the 2000 edition of the HCM (Table 2; TRB, 2000).

However, the author would point out that the upper and lower boundaries of walking speeds in the defined LOS ranges are not constant but rather they vary across the LOS ranges. As can be seen from Table 2.2, as the LOS range drops from the highest point (LOS range F) the difference between the upper and lower boundaries of walking speeds becomes narrower. Base on the figures in Table 2.2, which are quoted in the HCM, the difference between, for example, LOS ranges B and A is only 0.03 m/s. Similarly, the difference between LOS ranges B and C is only 0.05 m/s. The author would argue that these are very small margins, and that the analysis in this thesis has shown that the HCM methodology can produce results that could result in decisions being made that have implications to the design process.

For example, if speed was used rather than flow as the definition of LOS, then there is a possibility that the wrong LOS was identified as being required. This is entirely feasible, since the model validation exercises in Chapter Seven showed that at low to medium LOS ranges the HCM methodology consistently over-estimated speeds. This in turn could result in an over-designed infrastructure with unnecessary cost implications. Furthermore, the author would argue that he has seen anecdotal evidence that refined estimates of walking speeds can improve the accuracy of estimates in pedestrian demand levels, from the point of view of pedestrian transport software models. Section 8.6.1.2 describes a case study of a real-life modelling project where more refined estimates of walking speeds would have helped identify suitable levels of demands for pedestrians across a major city centre walking network. This software model was used in the validation exercise in this thesis and was shown to improve pedestrian flow estimates across the area (see Chapter Seven and Appendix Four).

Another point to note is that the HCM methodology is an average relationship for generic pedestrian flows and their associated characteristics. Chapter Two showed the development of the 2000 edition of the HCM from the 1994 version (see Section 2.2.2.2 to 2.2.2.4) and Chapter Six set out a series of comparisons of the new data collected for this thesis with the established theories that underpinned the development of the relationships in the HCM (see Section 6.3.2.1 to 6.3.2.5).

Various sections of the HCM show how adjustments can be made to the generic relationship to reflect different proportions of pedestrians (e.g. for elderly pedestrians see Section 2.2.2.2 in Chapter Two), but these are limited in how they account for the many varying characteristics of pedestrian flows. These differences can be seen when looking at the theories used to develop the HCM relationships. The research used to develop the generic HCM methodology was based on studies by various researchers including Pushkarev and Zupan (1975a and 1975b) and Fruin (1971). Figures 6.1a to 6.4a in Chapter Six shows that these studies are actually based on data for different types of pedestrians and include commuters, shoppers and students amongst others. As can be seen from Figures 6.1a to 6.4a, there are clearly differences in walking speeds between different pedestrian characteristics yet there is only one generic relationship in the HCM for average pedestrian proportions rather than separate relationships for individual types of pedestrians. One of the main advantages of the new Full Base Model and its variant developed in this thesis is that they take account of different pedestrian characteristics, much more than the HCM methodology, which will therefore help planners with the design process.

8.6.1.2 Case Study of a Real-life Project

To further explain the benefits of the new models, Appendix Four shows a real-life application of a PEDROUTE model of the walking network in the city centre of Edinburgh (Halcrow, 2000). The model was used to design improvements to the network to make it easier and safer to walk thereby making walking a more attractive mode of travel.

The planners first tried to reproduce the existing pedestrian flows by determining the routes people are currently using in the existing layout of the network. Once the model was set up, they then sought to identify areas which could be made safer and more accessible, and devised a series of geometric improvements. What the planners found, however, were difficulties in calibrating the PEDROUTE representation of existing pedestrian flows through the network to reflect actual observed flows and associated travelling conditions on-the-ground (Halcrow, 2000). This was because speed was used as the main route-choice factor determining which routes people take. In fact, speed has been shown to be the main factor used in the industry models (see Section 2.3.2 in Chapter Two). In the PEDROUTE model, as with other models, walking speed is estimated using the HCM methodology, which has been shown in this thesis to only represent just over half the variations that affect speed. Clearly, if the estimate of the routes through a network are flawed then the analysis and resultant design can be undermined. Furthermore, their analysis was also limited to examining how flows and speeds are influenced by the limited geometric parameters used by the HCM methodology, and could therefore only examine how these limited number of variables interact with each other and effect walking patterns.

This drawback led them to repeat the analysis some time later so they could improve the accuracy of the analysis by examining the effects of additional factors (Halcrow, 2002c). However, this was still using the HCM methodology which is only explaining just over half the variations in walking speeds. This can lead to potentially large errors. Even though the analysis was undertaken again with more data, the design is arguably sub-optimal. This was shown in this thesis in Chapter Six, when the HCM methodology was tested using a significantly larger set of data, and was found to only marginally improve its level of accuracy. If they had used the new models in this thesis they would have obtained significantly better levels of accuracy, especially the Full Base Model which has been shown to explain almost double the variations in speed than the HCM methodology. It is not just accuracy that benefits, but also the design process since the resultant geometric designs obtained from the new models are arguably more suited to the different needs of pedestrians. Even with the extra costs of data collection, the benefits of using the new models would have saved the planners time (and additional study and survey costs) in the long-run.

Additionally, the extra factors they collected included the effects of different land-uses, relocating bus facilities, restrictions due to geometric layouts and different travel times. The new models developed in this thesis are been able to examine all of these factors and more. In addition to the basic HCM inputs of flow and density, the Full Base Model contains 13 variables covering a number of geometric parameters, different land-uses, the effects of bus facilities, different travel times, varying walking areas and environmental conditions (both built and natural).

Not only could the Full Base Model have been used to help with their study, but it would have also given a deeper insight into the interactions of all of these factors as it contains these variables in one statistical relationship thereby allowing the planner to see how changing values of one parameter or a combination of parameters effects the results.

The new models developed in this thesis are ideally suited for inclusion in these software programs, and have been shown in Chapter Seven to be able to be used in conjunction with current industry software models like PEDROUTE. Furthermore, the new models can also easily be used by themselves.

8.6.1.3 New Scenarios where the New Models could be Used

While the above example in Section 8.6.1.2 is a major step forward, there are a few other situations in which the new models can be used. These include:

- accessibility analysis models which use an estimate of speed as one of the measures of how easy it is to access an area. Furthermore, this can also be analysed for different types of pedestrians and walking environments, and the new models can estimate speeds for these scenarios;
- estimating the effects of different types of pedestrians on walking speed. This is commonly used in micro-simulation applications and associated software models, which require an estimate of speed for each type of pedestrian;
- public transport assignment models which estimate the routes people use to walk to and from public transport stations and stops. Speed is one of the main factors used in this; and

- land-use planning including estimating the needs of pedestrians for new developments. Current procedures include applying trip generation equations which use trip rates, land-use areas and some factor representing the level of accessibility to the area (e.g. speed).

The new models are an improvement on the speed-estimation models used in the above analysis. For example, in the case of public transport assignment (the third example above), it is common practice to use a simplified speed/flow function to estimate an average speed based on an assumed or observed flow. These functions do not include any of the effects of pedestrian characteristics, environment or geometry, as shown to be influential in this research.

It is acknowledged, however, that the HCM methodology allows for more disaggregated models of walking speeds for various subgroups within the pedestrian flow to be developed. Similar disaggregated modelling could also have been undertaken in this thesis, but would not have allowed for the examination of the key variables being investigated in this thesis (focus on the aims of this study). This also allowed the author to develop a practical set of models with manageable data needs. Future research, however, could examine the potential for developing disaggregated sub-models by constructing new separate sub-models.

8.6.2 Trade-off between Cost and Accuracy

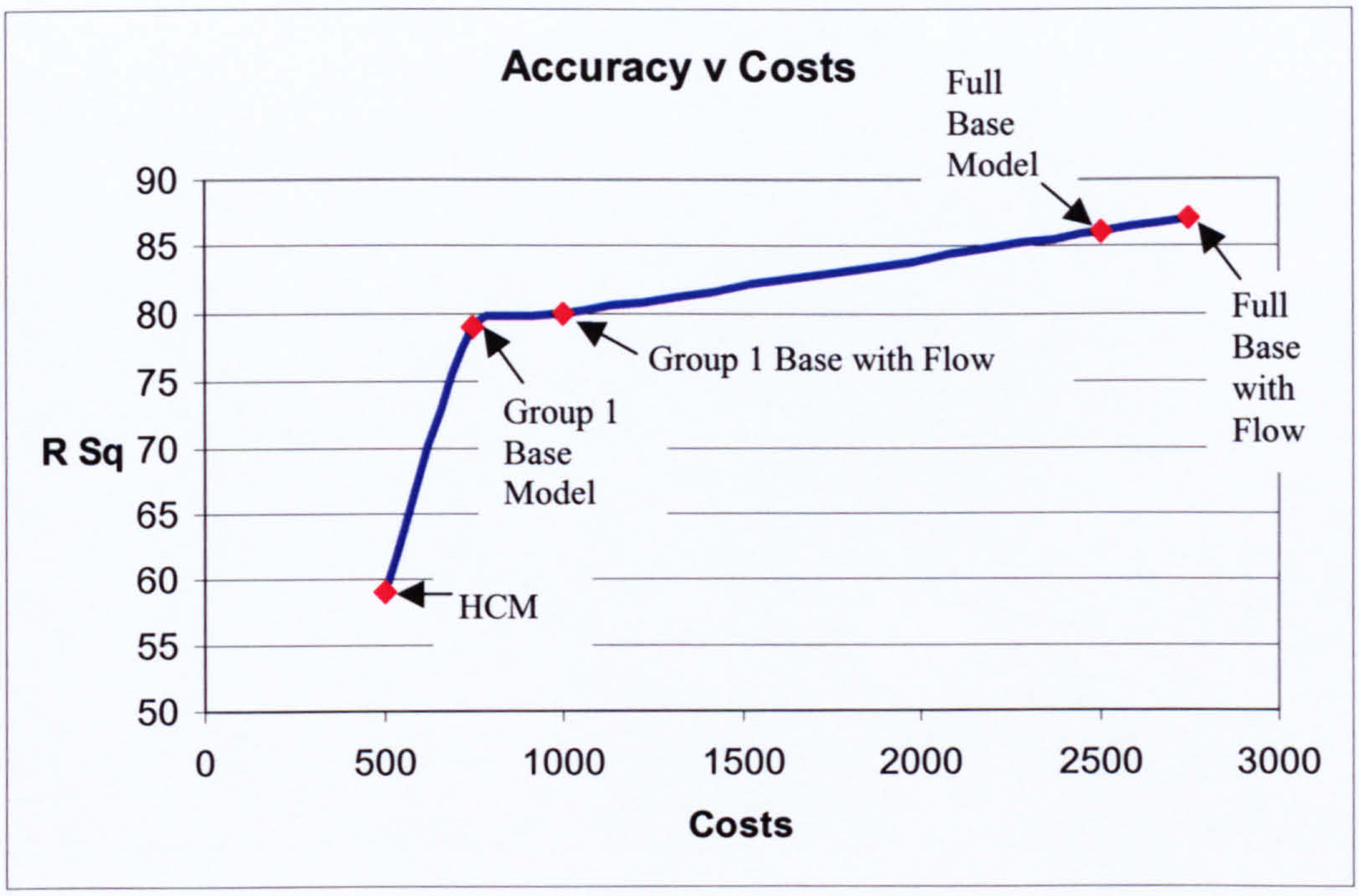
Depending on which of the 4 models categorised in Section 8.6.1 above is selected, the new models include up to 13 variables in addition to pedestrian flows and density. While the new models have been shown to produce significantly better results than the HCM methodology, there is a trade-off between the accuracy of the estimates and the number of variables which require data, with the subsequent consequences of the availability of suitable data or the costs of collecting new data if it is not available.

For example, the basic Geometric-based Model requires very little survey equipment and can in fact be used with simple manual data collection techniques (e.g. pedestrian counts). This model could therefore be used with minimal survey staff, manually counting pedestrian flows and visually observing the site layout. In the Full Base Model, however, some of the variables could require video surveys (e.g. details of the pedestrian characteristics) to gather the required volume of information. Time to process the videotapes would then be required in addition to the time required to undertake the analysis, thereby increasing the total study time and associated costs.

8.6.2.1 Estimated Costs of the Improved Accuracy

To help emphasis the discussion in the previous Section on the trade-off between accuracy and costs of using the new models, Figure 8.1 shows a comparison of the improvements in accuracy of the new models compared with the HCM methodology. Also shown in Figure 8.1 are estimates of the costs of using the various models, again compared to the HCM methodology. These costs have been based on an assumed cost of £500 per day for a suitably experienced transport planner or designer.

Figure 8.1: Comparison of Accuracy versus Costs



As can be seen from Figure 8.1, there is a quick gain in accuracy when using the Group 1 Basic Model over the HCM methodology but further gains in accuracy soon level off as the costs rise significantly. However, there are still significant improvements in accuracy to be gained over cost implications by using the Group 1 Basic Model instead of the HCM methodology.

8.7 Critique and Limitations

While the new models developed in this thesis have been found to be an improvement on existing methodologies, it is important to point out their weaknesses. This will help transport planners and engineers when potentially using them since, provided these limitations are known and understood, they can be accounted for if the new models are used. In addition, discussing the drawbacks of the new models helped to identify further areas of research.

8.7.1 Potential Weaknesses in the Data Collection Process

The limitations of the new models include observational weaknesses when collecting some of the data they require. While most of the data can be measured (e.g. flow, walkway width, etc) others are subjective. For example, age was obtained by visual inspection of the pedestrian. Clearly, different people might have varying opinions as to which banding to classify the same pedestrian.

Another restriction is due to the ranges of the data used to develop the new models. The new models were developed using data collected from a sample of surveys. While this data was found to be very comprehensive and covered most travel conditions (including all LOS ranges), the new models presented in Chapter Six were based on data with known ranges and characteristics. In particular, the new models might not produce suitable estimates if some of the key variables are outside the ranges of the input data used to develop them. The suitable ranges of the key variables of the new models are shown in Table 6.17 of Chapter Six.

8.7.2 Models only suitable for UK Applications

The data collected and used to develop the new models were based on observations in UK cities. This can be seen as a limitation, since the literature review in Chapter Two showed that different population features in different countries exhibit different walking characteristics. This suggests the new models might not be suitable for use in other countries.

8.7.3 Models only suitable for Limited Walking Environments

The new models are developed from data of on-street public areas. These included shopping streets (both pedestrianised and non-pedestrianised), central business districts (office locations) and residential areas. The new models therefore might not be suitable for other walking environments, such as public transport stations.

8.8 Recommendations for Further Research

The positive results of this research have opened up the possibility for further work which will bring added value and further enhance the understanding of pedestrian movements. Based on the discussion on the limitations of the new models in Section 8.6, they can be summarised as follows:

- models based on data from other countries; and
- models covering other walking environments.

These are discussed below.

8.8.1 Models based on Data from Other Countries

As previously mentioned, the new models developed in this research have been based on data collected from UK cities and might not be applicable in other countries, since the literature review showed different walking characteristics in different countries.

It would be beneficial to conduct further research using data from other countries, with a view to identifying how the new models would change using this data. It might not be feasible to use the new models in other countries, and it is possible that new models would be required for other countries.

8.8.2 Models covering Other Walking Environments

The data used to develop the new models focussed on uncovered public streets, including residential locations, CBD's, shopping streets and pedestrianised areas. They might only be suited to these types of walking environments, but there is scope for assessing other types of pedestrian environments and developing similar structured models of walking speeds. Other types of walking areas could include:

- public transport passenger stations (e.g. bus stations and rail stations);
- buildings (e.g. offices, large retail sites, etc); and
- special pedestrian walking facilities (e.g. footbridges).

While there has been considerable research carried out for different public transport facilities, the literature review has suggested that this has tended to focus on similar types of environments or similar types of facility. For example, the HCM has specific parameters for analysing Airport Terminals (HCM, 2000) and others have researched and prepared guidelines for underground stations (e.g. LUL, 1997).

However, these are not the only types of passenger interchanges. In the case of rail there seems to be less research on surface rail stations. The author believes it is wrong to apply parameters developed using underground stations to analyse surface rail stations even though they are both railway stations. Similarly, there is a need to look at bus stations more. In buildings, research seems to have concentrated on critical levels of flows for large stadiums (e.g. Still, 2000) but little on moving around general purpose buildings, in particular walking along corridors while interacting with furniture.

8.9 Conclusions

This thesis has shown that there is a lack of understanding of how the many different environmental factors and pedestrian characteristics interact to affect walking speeds and the extent to which variations occur both within and between different walking conditions.

The findings of the literature review suggest that the current practices do not fully understand or take cognisance of all the issues. It is clear from both the initial analysis (pilot study) and the more comprehensive analysis there are many characteristics of pedestrian movements which when added significantly improve the estimates of walking speeds, even though they currently do not form part of existing practices and guidelines.

A set of new models have been developed and validated against independent data, and have been shown to significantly improve estimates of walking speeds thereby improving pedestrian modelling forecasts. These models have been recommended for use and also categorised into a hierarchy to show which conditions are most appropriate for their application.

REFERENCES

Adler, J L and Blue, B J (1999) "*Bi-directional emergent fundamental pedestrian flows from cellular automata microsimulation*", International Symposium on Transportation and Traffic Theory, PP235-254

Adler, J L and Blue, B J (2000) "*Modelling four-directional pedestrian flows*", Transportation Research Record 1710, PP20-27

Alder J.L. and Blue, V. (2001) "*Cellular Automata Microsimulation for Modeling Bi-directional Pedestrian Walkways*", Transportation Research B 35, pp. 293-312

Al-Masaeid, H R; Al-Suleiman, T I; Nelson, B C (1993) "*Pedestrian Speed-Flow Relationship for Central Business District Areas in Developing Countries*", Transportation Research Record 1396, PP69-74

Ando, K. Aoki, T, Oto, H (1992) "*Development of the prediction System for Passenger Flow*", Quarterly Review of the Rail Technical Research Institute Report, Japan

Annesley, T; Daly, P; McGrath, F (1991) "*Pedestrian Speed/Flow relationships for underground stations*", Traffic Engineering and Control, February 1991

Annesley, T; Dix, M; Beswick, A; Buchanan, P (1989) "*Development and application of pedestrian assignment models*", Traffic Engineering and Control, July/August 1989

Aoki, T (1994) "*The simulation system of passenger flow*", Quarterly Review of Rail Technical Research Institute, Vol 35, No 2, May 1994

Bendixson, T (1997) "*Walking to Happiness*", Surveyor, 2 October, pp 22-23

Benz, G and Fruin, J (1984) "*Pedestrian Time-Space Concept for Analyzing Corners and Crosswalks*", Transportation Research Record 959, Transportation Research Board, USA

Botma, Hein (1995) "*Method to Determine Levels of Service for Bicycle Paths and Pedestrian-Bicycle Paths*", Transportation Research Record 1502, Transportation Research Board

Bowman, Brian and Vecellio, Robert (1994) "*Pedestrian Walking Speeds and Conflicts at Urban Median Locations*", Transportation Research Record 1438, Transportation Research Board

Brilon, Werner (1994) "*A New German Capacity Manual*", The Second International Symposium on Highway Capacity, 1994 Proceedings

Buckman, L; Leather, A (1994) "*Modelling station congestion the PEDROUTE way*", Traffic Engineering and Control, June 1994

Canter. D (1985) "*Studies of Human Behaviour in Fire: Empirical results and their implications for Education and Design*", BRE Document 61, UK

Chartered Institute of Transport (2000) "*Guidelines on Interchange Design*", Colin Buchanan and Partners, CIT Press, UK

Christie, N (1995) "*The High Risk Child Pedestrian: Socio-economic and Environmental Factors in their Accidents*", TRL Project report 117, Transport Research Laboratory, Crowthorne, UK

Citilabs (2002) "*CUBE Voyager Users Manual*", Citilabs Limited, San Francisco, USA

City of Westminster Council (1996), *"Oxford Street Enhancement Study"*, London, UK

Clifford. P (1999) "*Tynecastle football stadium crowd movement simulation*", Stadia and Arenas: Development, design and management. Stadia & Arenas 2000, 16-17th June 1999. London Arena. The Concrete Society

Coffin, A; Morall, J (1995) "*Walking Speeds of Elderly Pedestrians at Crosswalks*", Transportation Research Record 1487, Transportation Research Board

Cohen, E (1997) "*Simulation of Human Flow with Particle Systems*", ArSciMed. 07 Rue de Bercy, 75012 Paris, France

Cullen, P (1997) "*To Share or Not to Share?*", Walk, Vol 8, No 3. Pedestrians Association, London, UK

Daamen, W. (2002), "*SimPed: a Pedestrian Simulation Tool for Large Pedestrian Areas*", EuroSIW Conference Proceedings, 24-26 June 2002

Daamen, W. and S.P. Hoogendoorn (2002) "*Modeling pedestrians flows through transfer stations*", Paper Number 02-2674, Transportation Research Board Annual Meeting 2002, USA

Daamen, W. and Hoogendoorn, S.P. (2003a), "*Experimental Research on Pedestrian Walking Behavior*", 82nd Annual Meeting at the Transportation Research Board, USA

Daamen, W and Hoogendoorn, S.P. (2003b), "*Extracting Microscopic Pedestrian Characteristics from Video Data*", 82nd Annual Meeting at the Transportation Research Board, USA

Davis, Dennis and John Braaksma (1987) "*Level-of-Service Standards for Platooning Pedestrians in Transportation Terminals*", ITE Journal, Institution of Transportation Engineers (ITE), April 1987, USA

Department of the Environment, Transport and the Regions (1997) "*Developing an Integrated Transport Policy - Factual Background*", Department of the Environment, Transport and the Regions, London, UK

Department of the Environment, Transport and the Regions (1998) "*A New Deal for Transport: Better for Everyone*", Transport White Paper, HMSO, UK

Department of the Environment, Transport and the Regions (1999) "*Control of Major-Accident Hazards) Regulations 1999*", HMSO, London, UK

Department of the Environment, Transport and the Regions (2000) "*Transport 2010: The 10 Year Plan*", HMSO, London, UK

Department of Transport (1996) "*Developing a Strategy for Walking*", HMSO, London, UK

Department of Transport Local Government and the Regions (2001) "*Focus on Personal Travel*", The Stationary Office, London, UK

Dixon, L B (1996) "*Bicycle and Pedestrian Level of Service Performance Measures and Standards for Congestion Management Systems*", Transportation Research Record 1538, Transportation Research Board, USA

Dixon, Linda B. (1996) "*Bicycle and Pedestrian Level of Service Performance Measures and Standards for Congestion Management Systems*", TRB Annual Meeting, USA

Edlmann, T. and T. K. Pitcairn, T. K. (2000) "*Individual differences in road crossing ability in young children and adults*", British Journal of Psychology, British Psychological Society, Volume 91, Part 3, August 2000, pp391-410, UK

Fruin, John J (1971), "*Pedestrian Planning and Design*", Metropolitan Association of Urban Designers and Environmental Planners, New York, USA

Galea E.R (1997a) "*The numerical simulation of aircraft evacuation and it's application to aircraft design and certification*", Paper No. 97/IM/28, CMS Press, The Fire Safety Engineering group. Centre for Numerical Modelling and Process Analysis, University of Greenwich. Wellington Street, London SE18 6PF, UK

Galea E.R (1997b) "*Use of mathematical modelling in fire safety engineering*", Paper No 97/IM/25. CMS Press. The Fire Safety Engineering group. Centre for Numerical Modelling and Process Analysis, University of Greenwich. Wellington Street, London, SE18 6PF, UK

Gaffron, P (2002) *"The implementation of walking and cycling policies in British local authorities"*, PhD Thesis, School of Built Environment, Napier University, Edinburgh, UK.

Halcrow (2000) "Edinburgh City Centre Pedestrian Surveys", Halcrow Group Limited, Edinburgh, UK

Halcrow (2000) "Edinburgh City Centre PEDROUTE Model", Halcrow Group Limited, Edinburgh, UK

Halcrow (2002a) "*PEDROUTE Pedestrian Model*", Halcrow Group Limited, London, UK (http://www.halcrow.com/pdf/urban_reg/redrt_broch.pdf)

Halcrow (2002b) "*PAXPORT Passenger Simulation Model*", Halcrow Group Limited, London, UK (http://www.halcrow.com/pdf/urban_reg/pasport_broch.pdf)

Halcrow (2002c) "Edinburgh City Centre PEDROUTE Model: Re-Calibrated Upgrade Version", Halcrow Group Limited, Edinburgh, UK

Hankin, B; Wright, R (1958) "*Passenger flow in subways*", Operational Research Quarterly, Vol 9, No. 2, June 1958, pp81-88

Harris, N (1991) "*Modelling walk link congestion and the prioritisation of congestion relief*", Traffic Engineering and Control, February 1991, UK

Helbing, D (1995) "*Social force model for pedestrian dynamics*", Physical Review E, May, 1995

Helbing, D (1997) "*Modelling the evolution of human trail systems*", Nature 388

Helbing, D. (1992) "*A Fluid-dynamic model for the movement of Pedestrians*", Complex Systems 6, pages 391-415

Her Majesty's Railway Inspectorate (2002), New Works Section, Floor 4SW, Rose Court, Southwark Bridge London, SE1 9HS, UK

Hoel, L (1968) "*Pedestrian travel rates in Central Business Districts*", Traffic Engineering and Control, January 1968, UK

Hoogendoorn, S.P. (2003), "*Microscopic Simulation of Pedestrian Flows*", 82nd Annual Meeting at the Transportation Research Board, USA

Hoogendoorn, S.P. and P.H.L. Bovy (2002) "*Pedestrian Travel Behaviour in Walking Areas by Subjective Utility Optimization*", Paper nr. 02-2667. Transportation Research Board Annual Meeting 2002, USA

Institute of Transportation Engineers (1976) "*Characteristics and Service Requirements of Pedestrians and Pedestrian Facilities*", ITE Technical Council Committee 5-R Informational Report, Traffic Engineering, May 1976, USA

Institution of Highways and Transportation (1997), "*Transport in the Urban Environment*", IHT Press, London, UK

Institution of Highways and Transportation (2000), "*Guidelines for Providing for Journeys on Foot*", IHT Press, London, UK

Kaplan, R, Kaplan, S and Ryan, R (1998) "*With People in Mind*", Island Press, Washington, USA

Ketchell, N and Cole, S. (1993) "*The EGRESS code for human movement and behaviour in emergency evacuations in Engineering for Crowd Safety*", Elsevier, (Ed Smith RA, Dickie J) ISBN 0 444 899200

Khisty, C. Jotin (1982) "*Pedestrian Cross Flows in Corridors*", Transportation Research Record 847, Transportation Research Board, USA

Khisty, Jotin C. (1994) "*Evaluation of Pedestrian Facilities: Beyond the Level-of-Service Concept*", Transportation Research Record 1438, TRB, National Research Council, Washington, DC, USA

Knoblauch, R., M. Nitzburg, R. Dewar, J. Templer, and M. Pietrucha (1995) "*Older Pedestrian Characteristics for Use in Highway Design*", Office of Safety and Traffic Operations Research and Development, Federal Highway Administration, February 1995

Krzanowaski, W. J. (1998) *"An Introduction to Statistical Modelling"*, Arnold, London, UK

Lam, W H K, Cheung, C (2000) "*Pedestrian Speed-Flow Relationships for Walking Facilities*", Journal of Transportation Engineering, PP343-349, Volume 126, No 4

Lautso, K; Murole, P A (1974) "*Study of Pedestrian Traffic in Helsinki: Methods and Results*", Traffic Engineering and Control, pp 434 to 438, January 1974, UK

Lautso, Kari and Pentti Murole. (1974) "*A Study of Pedestrian Traffic in Helsinki: Methods and Results*", Traffic Engineering and Control, January 1974, UK

Leake, GR, AD May, and T Parry (1991) "*An Ergonomic Study of Pedestrian Areas for Disabled People*", TRRL Contractor Report 184, Transport Research Laboratory, Crowthorne, UK

London Underground Limited (1990) "*Station Planning Manual*", London, UK

London Underground Limited (1993) "*Station Planning Manual*", London, UK

London Underground Limited (1995) "*Annual Report*", London, UK

London Underground Limited (1997) "*Station Planning Manual*", London, UK

Lovas, G (1994) "*Modelling and Simulation of Pedestrian Traffic Flow*", Transportation Research Part D; Methodological, Volume 28, Issue 6

Lu, Y-J; Yuan, X; Yan, C-B (1992) "*Image Sequence Analysis for Measurement of Pedestrian Flows*", Journal of the Transportation Research Forum, Volume 32, Issue 2, PP399-408

MacDorman, A (1977) "*Characteristics of walking speeds in the CBD of Washington, D.C*", Transportation Research Record, USA

May, AD and Hopkinson, PG (1991) "*Perceptions of the Pedestrian Environment*", TRRL Contractor Report 148 Transport and Road Research Laboratory, Crowthorne, UK

Maylor, Elizabeth A.; Allison, Sue; Wing, Alan M. (2001) "*Effects of spatial and non-spatial cognitive activity on postural stability and walking*", British Journal of Psychology, British Psychological Society, Volume 92, Part 2, May 2001, pp319-339, UK

McLeod, Douglas S (2000) "*Multi-modal Arterial Level of Service*", presented by Rick Dowling at the Fourth International Symposium on Highway Capacity, Maui, Hawaii, July 1, 2000; proceedings published by TRB in Transportation Research E-Circular E-C018, Washington, DC

Milazzo, J S; Rouphail, NM; Hummer, J E; Allen, D P (1999) "*Quality of Service for Interrupted-Flow Pedestrian Facilities*", Transport Research Record, USA, PP25-31

Morrall, John F.; Lam, William H.K.; and Herbert Ho. (1995) "*Pedestrian Flow Characteristics in Hong Kong*", Transportation Research Record 1487, Transportation Research Board, USA, pp56-62

Murray, K (1986) "*The Characteristics of Walking and Age*", Transportation Research Record, USA

Naderi J (2002) "*On the nature of Walking and Learning Pedestrian Environment*", Selected at The Architectural Research Centers Consortium (ARCC), Montreal, Canada

Naderi, J, Raman, B (2002) "*Design Considerations in Simulating Pedestrian Environments*", Transportation Research Board, Washington, USA

Navin, Francis P.D. and R. J. Wheeler. (1969) "*Pedestrian Flow Characteristics*", Traffic Engineering, June 1969, UK

Nitzburg, Marsha; Knoblauch, Richard; and Martin Pietrucha (1996) "*Field Studies of Pedestrian Walking Speed and Start-up Time*", Transportation Research Record 1538, Transportation Research Board, USA

Oeding, D (1963) "*Verkehrsbelastung und Dimensionerung von Gehwegen und anderen Anlagen des Fussgaengerverkehrs*", Strassenbau und Strassenverkehrstechnik No 22, Bonn, Germany

Office for National Statistics (1992 to 2001) "*Annual Labour Force Survey*", HMSO, UK

O'Flaherty, C. A; Parkinson, M. H (1972) "*Movement on a City Centre Footway*", Traffic Engineering and Control, pp 434 to 438, February 1972, UK

Older, S (1964) "*Pedestriand*", Dept of Scientific and Industrial Research, Road Research Laboratory, Publication No LN 275/SJ0, Berkshire, UK

Older, S. J (1968) "*Movement of Pedestrians on Footways in Shopping Streets*", Traffic Engineering and Control, pp 160 to 163, August 1968, UK

Pickett, MW (1979) "*Improving the Town Centre of York*", TRRL PA 3056. Transport Research Laboratory, Crowthorne, UK

Polus, Abishai, Joseph Schofer, and Ariela Ushpiz. (1983), "*Pedestrian Flow and Level of Service*", Journal of Transportation Engineering, American Society of Civil Engineers, January 1983, USA

Pushkarev, Boris and Zupan, Jeffrey (1975a) "*Urban Space for Pedestrians*", The MIT Press, Cambridge, Massachusetts, USA

Pushkarev, Boris and Zupan, Jeffrey (1975b) "*Capacity of Walkways*", Transportation Research Record 538, Transportation Research Board, USA

Railtrack (1997) "*Station Design Manual*", Railtrack Plc, London, UK

Ratnayake, L; Morrall, J S; Seneviratne, P N (1991) "*Comparison of Central Business District Pedestrian Characteristics in Various Areas*", Transportation Research Record 1294, PP57-61, USA

Reading, IAD, Wan CL, Dickinson, KW (1995) "*Developments in Pedestrian Detection*", Traffic Engineering and Control 1995/10, pp 538-542, UK

Robertson, H. Douglas, Joseph Hummer, and Donna Nelson (1994) "*Manual of Transportation Engineering Studies*", Institute of Transportation Engineers, USA

Roddin, Marc (1981) "*NCHRP Report 240: A Manual to Determine Benefits of Separating Pedestrians and Vehicles*", Transportation Research Board, USA

Rouphail, Nagui, Joseph Hummer, Joseph Milazzo II, and D. Patrick Allen. (1998), "*Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual*", Federal Highway Administration Report, February 1998, USA

Sarkar, Sheila. (1993) "*Determination of Service Quality Levels for Pedestrians: With European Examples*", Transportation Research Record 1405, TRB, National Research Council, Washington, DC, USA

Sarkar, Sheila. (1996) "*An Evaluation method for Comfort Requirement in Outdoor Pedestrian Spaces*", TRB Annual Meeting, USA

Scottish Executive (2001) "*Scottish Transport Appraisal Guidance*", version 1.0, Scottish Executive, Edinburgh, UK

Scott Wilson Scotland Ltd (2002), "*Access Improvements to Railway Stations in West Dunbartonshire*", Glasgow, UK

Sime J. (1992) "*Crowd Safety Management and Communications in Disasters*", MoSHE. Available from the Building Research Establishment. Borehamwood or from JSA Research Consultants, Goldalming, Surrey, UK

Smith, S.A., K.S. Opeila, L.L. Impett, M.T. Pietrucha, R. Knoblauch, and C. Kubat. (1987) "*NCHRP Report 294A: Planning and Implementing Pedestrian Facilities in Suburban and Developing Rural Areas - Research Report*", Transportation Research Board, USA

Spokes (2003) "*Annual Survey of Local Authorities*", Spokes Newsletter, November 2003 Edition, UK

Steer Davies Gleave (2001) "*Review of Scottish Local Transport Strategies and Road Traffic Reduction Act Reports*", Scottish Executive, UK

Still, G K (2000) "*Crowd Dynamics*", PhD Thesis, University of Warwick, August 2000, UK

Tanaboriboon, Yordphol and Guyano, Jocelyn A. (1989) "*Level of Service Standards for Pedestrian Facilities in Bangkok: A Case Study*", ITE Journal, Institution of Transportation Engineers (ITE), November 1989, USA

Tanaboriboon, Yordphol, Sim Siang Hwa, and Chin Hoong Chor. (1986) "*Pedestrian Characteristics Study in Singapore*", Journal of Transportation Engineering, May 1986

The Scottish Office (1998) "*Travel Choices for Scotland*", Transport White Paper, HMSO, UK

Thompson, SJ and S Heydon (1991) "*Improving Pedestrian Conspicuity by Use of a Promontory*", Traffic Engineering and Control 1991/08, pp 472-478, UK

Transportation Research Board (1980) "*Interim Materials on Highway Capacity*", Transportation Research Circular 212, National Research Council, Washington, USA

Transportation Research Board (1994) "*Highway Capacity Manual*", Special Report 209, National Research Council, Washington, USA

Transportation Research Board (2000). "*Highway Capacity Manual*", Special Report 210, National Research Council, Washington, USA

Turvey, I. G; May, A. D; and Hopkinson, P. G (1987) "*Counting methods and sampling strategies for determining pedestrian numbers*", Institute for Transport Studies, ITS Working Paper 242, University of Leeds, UK

Turvey, I. G; May, A. D; and Hopkinson, P. G (1991) "*The measurement and prediction of pedestrian numbers*", Transport and Road Research Laboratory, Contractor Report 149, Crowthorne, UK

Virkler, Mark and Elayadath, Sathish (1994a) "*Pedestrian Speed-Flow-Density Relationships*", Transportation Research Record 1438, Transportation Research Board, USA, pp51-58

Virkler, Mark. (1996) "*Quality of Flow Along Pedestrian Arterials*", Combined 18th Annual Australian Road Research Board Transport Research Conference / Transit New Zealand Land Transport Symposium (at Christchurch, New Zealand), September 1996

Washington, S; Karlaftis, M; Mannering, F (2003) "*Statistical and Econometric Methods for Transportation Data Analysis*", Chapman and Hall/CRC, ISBN 1-58488-030-9, USA

Wegmann, F.J., K.W. Heathington, D.P. Middendorf, M.W. Redford, A. Chatterjee, and T.J. Bell (1983) "*NCHRP Report 262: Planning Transportation Services for Handicapped Persons - User's Guide*", Transportation Research Board, USA

Weidmann, U. (1993) "*Transporttechnik der Fussgaenger*", ETH, Schriftenreihe Ivt-Berichte 90, Zürich, German

White, J (1994) "*A Walk on the (not so) Wild Side - Promoting the Pedestrian in York*", PTRC Proceedings, Vol P381, pp 1-13, London, UK

Wigan, Marcus (1995) "*Treatment of Walking as a Mode of Transportation*", Transportation Research Record 1487, Transportation Research Board, USA

Willis, A., Kukla, R., Hine, J. and Kerridge, J. (2001) "*PEDFLOW: development of an autonomous agent model of pedestrian flow*", Transportation Research Record, USA

Willis, A., Kukla, R., Hine, J. and Kerridge, J. M. (2000) "*Developing the behavioural rules for an agent-based model of pedestrian movement*", Proceedings of the European Transport Conference, Proceedings P445, pp69-80

Young, S B (1999) "*Evaluation of Pedestrian Walking Speeds in Airport Terminals*", Transportation Research Record 1674, USA, PP20-26

Zacharias, J (2000) "*Modelling Pedestrian Dynamics in Montreal's Underground City*", Journal of Transportation Engineering, Volume 126, No 4, pp405-412

Zegeer, CV, M Cynecki, J Fegan, B Gilleran, P Lagerway, H C Tan, and R Works, (1994) "*Summary Report on FHWA Study Tour for Pedestrian and Bicyclist Safety in England, Germany and The Netherlands*", Report No. FHWA-PL-95-006, Federal Highways Administration, Washington DC, USA

APPENDICES

APPENDIX 1 STATISTICAL ANALYSIS OF DATA FROM THE PILOT STUDY IN EDINBURGH

A1.1 Introduction

To identify differences between the LOS ranges, separate statistical relationships using the Highway Capacity Manual (HCM) methodology were developed for each set of data collected from the pilot study in Edinburgh.

To examine whether increasing the sample size improves the predictive power of the statistical relationship all the data was combined into one large data set and a fifth statistical relationship was developed using the combined data. To allow for some validation of the resultant relationships from the HCM methodology only 80% of the aggregated data was used to develop the relationships and 20% was used as a hold-out sample for testing the relationships.

The statistical relationships developed using the HCM methodology using Data Sets 1 to 4 are shown in Tables A1.1 to A1.4. Similarly, the statistical relationship developed using the HCM methodology for all the data combined is shown in Table A1.5.

A1.2 Analysis of Data Set 1

The statistical relationship developed using the HCM methodology with Data Set 1 is shown in Table A1.1.

Table A1.1: Best-fit HCM Relationship developed from Data Set 1

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	LNDEN	-.412	.044	-1.783	-9.278	.000
	LNFLOW	.145	.012	2.230	11.604	.000

a. Dependent Variable: LN_SPEED

b. Linear Regression through the Origin

Both variables used (total two-way flow and density) were found to be statistically significant at the 95% Confidence Level, and the parameter LNDEN (the natural logarithm of density) is right-signed suggesting the relationship is as one would expect. However, the HCM methodology only provided an adjusted R-square value of 48%, suggesting it is only accounting for less than half of the variation in pedestrian speed.

Estimates using the statistical relationship were undertaken using the 20% hold out sample. This gave a Pearson correlation coefficient between the predicted and observed of 0.557 and the mean absolute percentage error (MAPE) is 39.7%.

A1.3 Analysis of Data Set 2

The statistical relationship developed using the HCM methodology with Data Set 2 is shown in Table A1.2.

Table A1.2: Best-fit HCM Relationship developed from Data Set 2

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	LNDEN	-7.112E-02	.046	-.032	-1.542	.000
	LNFLOW	7.57E-02	.002	.906	43.422	.000

a. Dependent Variable: LN_SPEED

b. Linear Regression through the Origin

As with the previous analysis, both variables used were found to be statistically significant at the 95% Confidence Level, and the parameter LNDEN (the natural logarithm of density) is right-signed suggesting the relationship is as one would expect.

Unfortunately, the HCM methodology only provided an adjusted R-square value of 22%, suggesting it is only accounting for about one quarter of the variation in pedestrian speed. Estimates using the statistical relationship were undertaken using the 20% hold out sample, which gave a Pearson correlation coefficient between the predicted and observed of 0.617 and the mean absolute percentage error (MAPE) is 43.5%.

A1.4 Analysis of Data Set 3

The statistical relationship developed using the HCM methodology with Data Set 3 is shown in Table A1.3.

Table A1.3: Best-fit HCM Relationship developed from Data Set 3

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	LNDEN	-.147	.054	-.253	-2.750	.000
	LNFLOW	7.42E-02	.010	.719	7.805	.000

a. Dependent Variable: LN_SPEED

b. Linear Regression through the Origin

Both variables used in this analysis were found to be statistically significant at the 95% Confidence Level, and the parameter LNDEN is also right-signed as expected. However, the adjusted R-square value was only 20%, indicating it is only accounting for about one fifth of the variation in pedestrian speed. Estimates using the 20% hold out sample gave a Pearson correlation coefficient between the predicted and observed of 0.637 and the mean absolute percentage error (MAPE) is 44.1%.

A1.5 Analysis of Data Set 4

The statistical relationship developed using the HCM methodology with Data Set 4 is shown in Table A1.4.

Table A1.4: Best-fit HCM Relationship developed from Data Set 4

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	LNDEN	-.851	.110	-1.690	-7.706	.000
	LNFLOW	8.096E-02	.025	.714	3.256	.000

a. Dependent Variable: LN_SPEED

b. Linear Regression through the Origin

Again both variables were found to be statistically significant at the 95% Confidence Level, and the parameter LNDEN is right-signed as expected.

The adjusted R-square value increased slightly to 32%, suggesting the statistical relationship is only accounting for about one third of the variation in pedestrian speed.

Estimates using the 20% hold out sample gave a Pearson correlation coefficient between the predicted and observed of 0.625 and the mean absolute percentage error (MAPE) is 41.2%.

A1.6 Analysis of All Data Combined

To examine whether increasing the sample size improves the predictive power of the statistical relationship all the data was combined into one large data set and a fifth statistical relationship was developed using the combined data.

The statistical relationship developed using the HCM methodology with all the data combined is shown in Table A1.5.

Table A1.5: Best-fit HCM Relationship developed from All Data

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	LNDEN	-.263	.006	-.566	-44.709	.000
	LNFLOW	6.29E-02	.001	.716	56.555	.000

a. Dependent Variable: LN_SPEED

b. Linear Regression through the Origin

As with all the statistical relationships developed using the separate survey data, both variables were found to be statistically significant at the 95% Confidence Level. The parameter LNDEN (the natural logarithm of density) is also right-signed as expected.

The adjusted R-square value increased to 59%, the highest level of all the relationships. This suggests the statistical relationship is only accounting for over half the variation in pedestrian speed. Estimates using the 20% hold out sample gave a Pearson correlation coefficient between the predicted and observed of 0.52 and the mean absolute percentage error (MAPE) is 37.5%.

APPENDIX 2 DETAILS OF THE SITES SELECTED

A2.1 Introduction

A summary of the characteristics of the data obtained from the final selected sites is presented in Tables A2.1 to A2.6. The existence of more than one set of survey videotapes at the same site was regarded as acceptable given the relatively wide range of pedestrian characteristics possible within each site and the differences between sites of other attributes (such as flow level, proportion of elderly pedestrians, walkway width and adjacent land-use).

Table A2.1: Characteristics of Site A – Buchanan Street, Glasgow

Site	Data Set	Factors Identified from Literature Review for Examination		
		Environment, Time and Location	Geometry	Adjacent Land-Uses
Site A, Buchanan Street, Glasgow (Mixed Area)	1	• Winter = 1 • Peak = 1 (Thursday 1700-1800 hrs) • Rain = 0 • Weekday = 1 • Location = 3 (West Scotland)	• Gradient = 5% • Width = 2.5m • Length = 5m • Furniture = 0 • Guard_Rail = 1 • Entry_Exit = 0 • Shopping_Area = 1 • Residential_Area=0 • CDB_Area = 1 • Junction = 0	• Retail = 1 • House = 0 • Office = 1 • Vehicles=1 • Parking = 0 • Bus_Stop=0 • Bus_Lane=1
	2	• Winter = 1 • Peak = 1 (Friday 0800-0900 hrs) • Rain = 0 • Weekday = 1 • Location = 3 (West Scotland)		
	3	• Winter = 1 • Peak = 0 (Saturday 1400-1500 hrs) • Rain = 1 • Weekday = 0 • Location = 3 (West Scotland)		

Table A2.2: Characteristics of Site B – Sauchiehall Street, Glasgow

Site	Data Set	Factors Identified from Literature Review for Examination: Environment, Time and Location	Geometry	Adjacent Land-Uses
Site B, Sauchiehall Street, Glasgow (Shopping Area)	4	• Winter = 0 • Peak = 1 (Friday 1700-1900 hrs) • Rain= 1 • Weekday = 1 • Location = 3 (West Scotland)	• Gradient = 0% • Width = 4m • Length = 6.5m • Furniture = 1 • Guard_Rail = 0 • Entry_Exit=1 • Shopping_Area = 1 • Residential_Area=0 • CDB_Area=0 • Junction = 0	• Retail = 1 • House = 0 • Office = 0 • Vehicles=0 • Parking=0 • Bus_Stop=0 • Bus_Lane=0
	5	• Winter = 0 • Peak = 1 (Thursday 1700-1900 hrs) • Rain= 0 • Weekday=1 • Location = 3 (West Scotland)		
	6	• Winter = 0 • Peak = 0 (Saturday 1400-1600 hrs) • Rain = 1 • Weekday = 0 • Location = 3 (West Scotland)		

Table A2.3: Characteristics of Site C – Oxford Street, London

Site	Data Set	Factors Identified from Literature Review for Examination: Environment, Time and Location	Geometry	Adjacent Land-Uses
Site C, Oxford Street, London (Shopping Area)	7	• Winter = 0 • Peak = 1 (Friday 1700-1800 hrs) • Rain= 0 • Weekday = 1 • Location = 1 (London)	• Gradient = 0% • Width = 5.5m • Length = 6m • Furniture = 1 • Guard_Rail=1 • Entry_Exit=1 • Shopping_Area = 1 • Residential_Area=0 • CDB_Area=0 • Junction = 1	• Retail = 1 • House = 0 • Office = 0 • Vehicles=1 • Parking=0 • Bus_Stop=1 • Bus_Lane=1
	8	• Winter = 0 • Peak = 1 (Thursday 1600-1900 hrs) • Rain= 0 • Weekday = 1 • Location = 1 (London)		
	9	• Winter = 0 • Peak = 0 (Saturday 1400-1700 hrs) • Rain = 1 • Weekday = 0 • Location = 1 (London)		

Table A2.4: Characteristics of Site D – Temple Road, Newcastle

Site	Data Set	Factors Identified from Literature Review for Examination: Environment, Time and Location	Geometry	Adjacent Land-Uses
Site D, Temple Road, Newcastle (Residential Area)	10	• Winter = 0 • Peak = 1 (Friday 1700-1800 hrs) • Rain= 0 • Weekday = 1 • Location = 4 (North England)	• Gradient = 2% • Width = 2.5m • Length = 6m • Furniture = 0 • Guard_Rail=0 • Entry_Exit=0 • Shopping_Area = 0 • Residential_Area=1 • CDB_Area=1 • Junction = 1	• Retail = 0 • House = 1 • Office = 0 • Vehicles=1 • Parking=1 • Bus_Stop=0 • Bus_Lane=0
	11	• Winter = 0 • Peak = 1 (Thursday 1700-1800 hrs) • Rain = 1 • Weekday = 1 • Location = 4 (North England)		

Table A2.5: Characteristics of Site E – High Street, Basingstoke

Site	Data Set	Factors Identified from Literature Review for Examination: Environment, Time and Location	Geometry	Adjacent Land-Uses
Site E High Street, Basingstoke (CBD Area)	12	• Winter = 1 • Peak = 1 (Thursday 1600-1900 hrs) • Rain = 1 • Weekday = 1 • Location = 5 (South England outside London)	• Gradient = 0% • Width = 4m • Length = 7m • Furniture = 1 • Guard_Rail=1 • Entry_Exit=1 • Shopping_Area = 0 • Residential_Area=0 • CDB_Area=1 • Junction = 1	• Retail = 0 • House = 0 • Office = 1 • Vehicles=1 • Parking=1 • Bus_Stop=1 • Bus_Lane=0
	13	• Winter = 1 • Peak = 0 (Saturday 1400-1700 hrs) • Rain = 0 • Weekday = 0 • Location = 5 (South England outside London)		

Table A2.6: Characteristics of Site F – Princes Street, Edinburgh

Site	Data Set	Factors Identified from Literature Review for Examination		
		Environment, Time and Location	Geometry	Adjacent Land-Uses
Site F, Princess Street, Edinburgh (Shopping Area)	14	• Winter = 0 • Peak = 1 (Thursday 1600-1900 hrs) • Rain = 0 • Weekday = 1 • Location = 2 (East Scotland)	• Gradient = 0% • Width = 4.5m • Length = 6.5m • Furniture = 1 • Guard_Rail=0 • Entry_Exit=1 • Shopping_Area = 1 • Residential_Area=0 • CDB_Area=0 • Junction = 0	• Retail = 1 • House = 0 • Office = 0 • Vehicles=1 • Parking=0 • Bus_Stop=1 • Bus_Lane=1
	15	• Winter = 0 • Peak = 0 (Saturday 1400-1700 hrs) • Rain = 0 • Weekday = 0 • Location = 2 (East Scotland)		
	16	• Winter = 1 • Peak = 1 (Saturday 1400-1800 hrs) • Rain = 0 • Weekday = 0 • Location = 2 (East Scotland)		
	17	• winter = 1 • Peak = 1 (Monday 1400-1800 hrs) • Rain = 0 • Weekday = 1 • Location = 2 (East Scotland)		

APPENDIX 3 KEY CHARACTERISTICS OF DATA COLLECTED

A3.1 Introduction

Tables A3.1 to A3.17 show the key characteristics of the data obtained from Data Sets 1 to 17. Table A3.18 shows the key characteristics when all the data from the 17 Data Sets is combined together. The sample sizes obtained are as follows:

- Data Set 1 (from Survey 1) has 113 observations;
- Data Set 2 (from Survey 2) has 137 observations;
- Data Set 3 (from Survey 3) has 97 observations;
- Data Set 4 (from Survey 4) has 391 observations;
- Data Set 5 (from Survey 5) has 476 observations;
- Data Set 6 (from Survey 6) has 569 observations;
- Data Set 7 (from Survey 7) has 317 observations;
- Data Set 8 (from Survey 8) has 779 observations;
- Data Set 9 (from Survey 9) has 902 observations;
- Data Set 10 (from Survey 10) has 93 observations;
- Data Set 11 (from Survey 11) has 99 observations;
- Data Set 12 (from Survey 12) has 652 observations;
- Data Set 13 (from Survey 13) has 791 observations;
- Data Set 14 (from Survey 13) has 713 observations;
- Data Set 15 (from Survey 13) has 852 observations;
- Data Set 16 (from Survey 13) has 257 observations;
- Data Set 17 (from Survey 13) has 297 observations; and
- The total numbers of observations obtained from all 17 surveys was 7,535.

Table A3.1: Summary Statistics of the Data Set 1 – Site A, Buchanan Street, Glasgow

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	113	113	113	113	113	113	113	113
Mean	5.802	31.054	9.465	0.017	4.135	44.514	0.929	182.803
Std. Dev	1.473	11.631	3.545	0.224	1.494	16.080	0.277	54.615
Minimum	3.000	14.545	4.433	-0.429	2.500	26.911	0.588	115.748
Maximum	8.500	68.571	20.901	0.429	6.250	67.277	1.667	328.150

Table A3.2: Summary Statistics of the Data Set 2 – Site A, Buchanan Street, Glasgow

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	137	137	137	137	137	137	137	137
Mean	5.781	37.459	11.418	-0.007	3.793	40.824	0.927	182.470
Std. Dev	1.412	14.536	4.431	0.273	1.619	17.432	0.267	52.625
Minimum	2.700	11.707	3.568	-0.500	2.083	22.422	0.595	117.126
Maximum	8.400	88.889	27.093	0.500	6.250	67.277	1.852	364.567

Table A3.3: Summary Statistics of the Data Set 3 – Site A, Buchanan Street, Glasgow

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	97	97	97	97	97	97	97	97
Mean	5.687	22.285	6.792	0.008	4.661	50.170	0.934	183.850
Std. Dev	1.307	6.533	1.991	0.141	1.346	14.484	0.252	49.525
Minimum	2.700	11.852	3.612	-0.200	3.125	33.638	0.602	118.504
Maximum	8.300	45.000	13.716	0.200	6.250	67.277	1.852	364.567

Table A3.4: Summary Statistics of the Data Set 4 – Site B, Sauchiehall Street, Glasgow

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	391	391	391	391	391	391	391	391
Mean	6.092	34.961	10.656	0.002	2.660	28.629	1.117	219.824
Std. Dev	1.262	10.592	3.228	0.198	0.409	4.405	0.246	48.508
Minimum	3.700	15.385	4.689	-0.400	2.167	23.326	0.765	150.591
Maximum	8.500	68.421	20.855	0.400	3.250	34.984	1.757	345.866

Table A3.5: Summary Statistics of the Data Set 5 – Site B, Sauchiehall Street, Glasgow

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	476	476	476	476	476	476	476	476
Mean	6.139	34.193	10.422	-0.003	2.679	28.834	1.102	216.951
Std. Dev	1.187	9.706	2.958	0.198	0.394	4.241	0.229	45.161
Minimum	3.700	14.815	4.516	-0.400	2.167	23.326	0.765	150.591
Maximum	8.500	63.636	19.396	0.400	3.250	34.984	1.757	345.866

Table A3.6: Summary Statistics of the Data Set 6 – Site B, Sauchiehall Street, Glasgow

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	569	569	569	569	569	569	569	569
Mean	8.972	49.556	15.105	-0.007	1.126	12.118	0.733	144.339
Std. Dev	0.974	9.812	2.991	0.168	0.108	1.166	0.082	16.065
Minimum	6.900	27.184	8.286	-0.364	0.975	10.495	0.586	115.354
Maximum	11.100	82.857	25.255	0.364	1.300	13.994	0.942	185.433

Table A3.7: Summary Statistics of the Data Set 7 – Site C, Oxford Street, London

	Crossing Time	Average Two-Way Flow		Ratio of Flows	Pedestrian Space		Pedestrian Speed	
	(sec)	(person/min/m)	(person/min/ft)		(m^2/person)	(ft^2/person)	(m/s)	(ft/min)
N	317	317	317	317	317	317	317	317
Mean	9.799	41.158	12.545	0.012	0.686	7.383	0.618	121.585
Std. Dev	0.903	7.371	2.247	0.148	0.094	1.010	0.058	11.449
Minimum	8.100	25.926	7.902	-0.333	0.551	5.931	0.526	103.543
Maximum	11.400	60.465	18.430	0.333	0.871	9.376	0.741	145.866

Table A3.8: Summary Statistics of the Data Set 8 – Site C, Oxford Street, London

	Crossing Time	Average Two-Way Flow		Ratio of Flows	Pedestrian Space		Pedestrian Speed	
	(sec)	(person/min/m)	(person/min/ft)		(m^2/person)	(ft^2/person)	(m/s)	(ft/min)
N	779	779	779	779	779	779	779	779
Mean	9.704	41.436	12.630	-0.003	0.689	7.414	0.624	122.814
Std. Dev	0.915	7.445	2.269	0.154	0.096	1.033	0.059	11.698
Minimum	8.000	25.688	7.830	-0.333	0.551	5.931	0.526	103.543
Maximum	11.400	65.000	19.812	0.333	0.871	9.376	0.750	147.638

Table A3.9: Summary Statistics of the Data Set 9 – Site C, Oxford Street, London

	Crossing Time	Average Two-Way Flow		Ratio of Flows	Pedestrian Space		Pedestrian Speed	
	(sec)	(person/min/m)	(person/min/ft)		(m^2/person)	(ft^2/person)	(m/s)	(ft/min)
N	902	902	902	902	902	902	902	902
Mean	10.394	49.129	14.975	0.004	0.530	5.708	0.583	114.721
Std. Dev	1.008	9.828	2.996	0.163	0.021	0.226	0.057	11.271
Minimum	8.500	27.100	8.260	-0.368	0.500	5.382	0.488	96.063
Maximum	12.300	77.037	23.481	0.368	0.563	6.060	0.706	138.976

Table A3.10: Summary Statistics of the Data Set 10 – Site D, Temple Road, Newcastle

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	93	93	93	93	93	93	93	93
Mean	5.683	32.189	9.811	-0.030	4.833	52.027	1.146	225.576
Std. Dev	1.554	13.274	4.046	0.243	1.767	19.018	0.347	68.405
Minimum	2.900	12.152	3.704	-0.429	3.000	32.293	0.714	140.551
Maximum	8.400	74.483	22.702	0.429	7.500	80.732	2.069	407.283

Table A3.11: Summary Statistics of the Data Set 11 – Site D, Temple Road, Newcastle

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	99	99	99	99	99	99	99	99
Mean	6.022	33.759	10.290	-0.028	3.412	36.728	0.886	174.417
Std. Dev	1.356	11.911	3.630	0.237	1.380	14.855	0.249	48.995
Minimum	2.900	12.973	3.954	-0.500	2.083	22.422	0.595	117.126
Maximum	8.400	77.419	23.597	0.500	6.250	67.277	1.724	339.370

Table A3.12: Summary Statistics of the Data Set 12 – Site E, High Street, Basingstoke

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	652	652	652	652	652	652	652	652
Mean	6.098	24.109	7.349	-0.003	4.312	46.412	1.202	236.580
Std. Dev	1.259	7.769	2.368	0.236	0.720	7.754	0.268	52.761
Minimum	3.700	9.524	2.903	-0.429	3.500	37.675	0.824	162.205
Maximum	8.500	52.632	16.042	0.429	5.250	56.512	1.892	372.441

Table A3.13: Summary Statistics of the Data Set 13 – Site E, High Street, Basingstoke

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	791	791	791	791	791	791	791	791
Mean	8.949	24.976	7.613	0.009	3.041	32.732	0.792	155.882
Std. Dev	0.977	4.498	1.371	0.142	0.350	3.769	0.089	17.460
Minimum	6.900	14.545	4.433	-0.273	2.625	28.256	0.631	124.213
Maximum	11.100	37.838	11.533	0.273	3.500	37.675	1.014	199.606

Table A3.14: Summary Statistics of the Data Set 14 – Site F, Princess Street, Edinburgh

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	713	713	713	713	713	713	713	713
Mean	6.064	34.533	10.526	-0.013	2.683	28.885	1.119	220.326
Std. Dev	1.224	9.905	3.019	0.208	0.408	4.393	0.241	47.354
Minimum	3.700	14.286	4.354	-0.400	2.167	23.326	0.765	150.591
Maximum	8.500	73.684	22.459	0.400	3.250	34.984	1.757	345.866

Table A3.15: Summary Statistics of the Data Set 15 – Site F, Princess Street, Edinburgh

	Crossing Time (sec)	Average Two-Way Flow (person/min/m)	(person/min/ft)	Ratio of Flows	Pedestrian Space (m^2/person)	(ft^2/person)	Pedestrian Speed (m/s)	(ft/min)
N	852	852	852	852	852	852	852	852
Mean	8.867	50.453	15.378	0.003	1.126	12.124	0.742	146.062
Std. Dev	0.972	10.168	3.099	0.161	0.112	1.201	0.083	16.253
Minimum	6.900	28.571	8.709	-0.364	0.975	10.495	0.586	115.354
Maximum	11.100	82.192	25.052	0.364	1.300	13.994	0.942	185.433

Table A3.16: Summary Statistics of the Data Set 16 – Site F, Princess Street, Edinburgh

	Crossing Time	Average Two-Way Flow		Ratio of Flows	Pedestrian Space		Pedestrian Speed	
	(sec)	(person/min/m)	(person/min/ft)		(m^2/person)	(ft^2/person)	(m/s)	(ft/min)
N	257	257	257	257	257	257	257	257
Mean	9.839	60.206	18.351	0.007	0.493	5.303	0.666	131.198
Std. Dev	0.913	10.250	3.124	0.150	0.067	0.724	0.064	12.670
Minimum	8.000	36.842	11.229	-0.333	0.398	4.284	0.570	112.205
Maximum	11.400	92.500	28.194	0.333	0.629	6.771	0.813	160.039

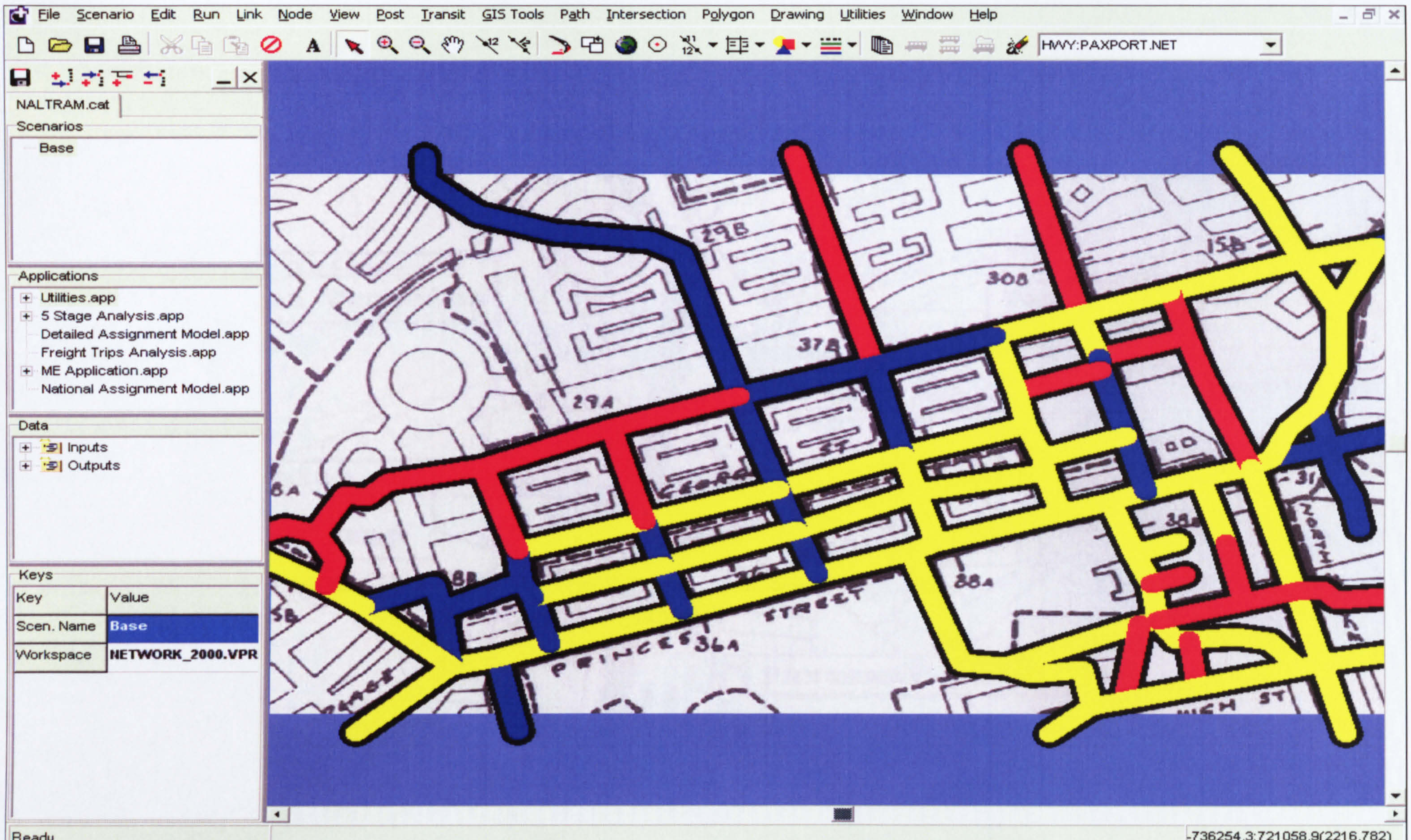
Table A3.17: Summary Statistics of the Data Set 17 – Site F, Princess Street, Edinburgh

	Crossing Time	Average Two-Way Flow		Ratio of Flows	Pedestrian Space		Pedestrian Speed	
	(sec)	(person/min/m)	(person/min/ft)		(m^2/person)	(ft^2/person)	(m/s)	(ft/min)
N	297	297	297	297	297	297	297	297
Mean	10.475	72.349	22.052	0.018	0.384	4.129	0.627	123.340
Std. Dev	1.026	14.535	4.430	0.167	0.015	0.161	0.063	12.336
Minimum	8.500	42.373	12.915	-0.368	0.361	3.886	0.528	103.937
Maximum	12.300	112.941	34.424	0.368	0.406	4.370	0.765	150.591

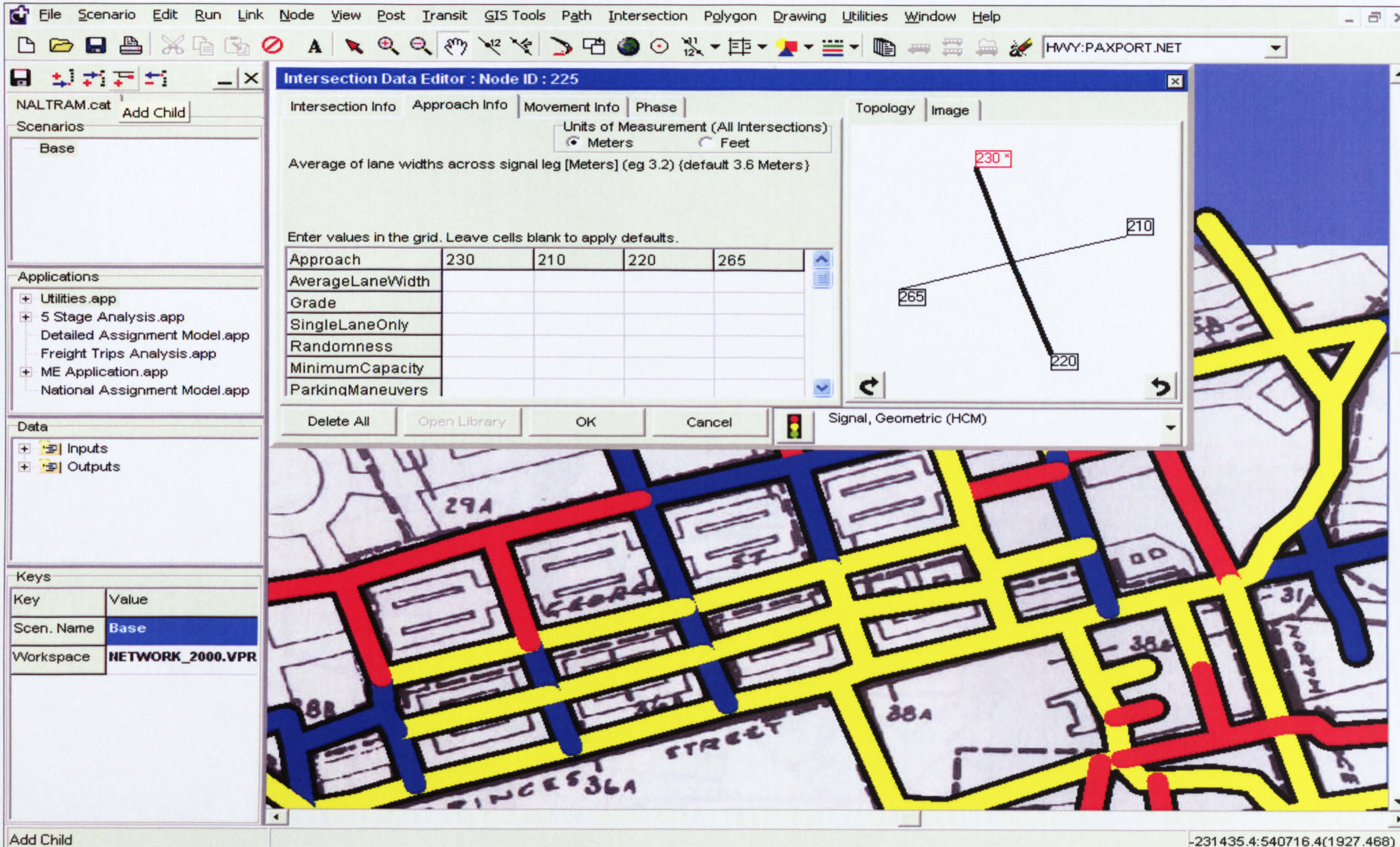
Table A3.18: Summary Statistics of All the Data Sets Combined

	Crossing Time	Average Two-Way Flow		Ratio of Flows	Pedestrian Space		Pedestrian Speed	
	(sec)	(person/min/m)	(person/min/ft)		(m^2/person)	(ft^2/person)	(m/s)	(ft/min)
N	7,535	7,535	7,535	7,535	7,535	7,535	7,535	7,535
Mean	8.248	40.473	12.336	0.003	1.957	21.063	0.836	164.594
Std. Dev	2.068	15.231	4.642	0.181	1.452	15.633	0.275	54.037
Minimum	2.700	9.524	2.903	-0.500	0.361	3.886	0.488	96.063
Maximum	12.300	112.941	34.424	0.500	7.500	80.732	2.069	407.283

	Edinburgh Pedestrian Study Overview of PEDROUTE Model Area	Appendix 4	Figure A4.1



	Edinburgh Pedestrian Study Network Coded for PEDROUTE Model	Appendix 4	Figure A4.2

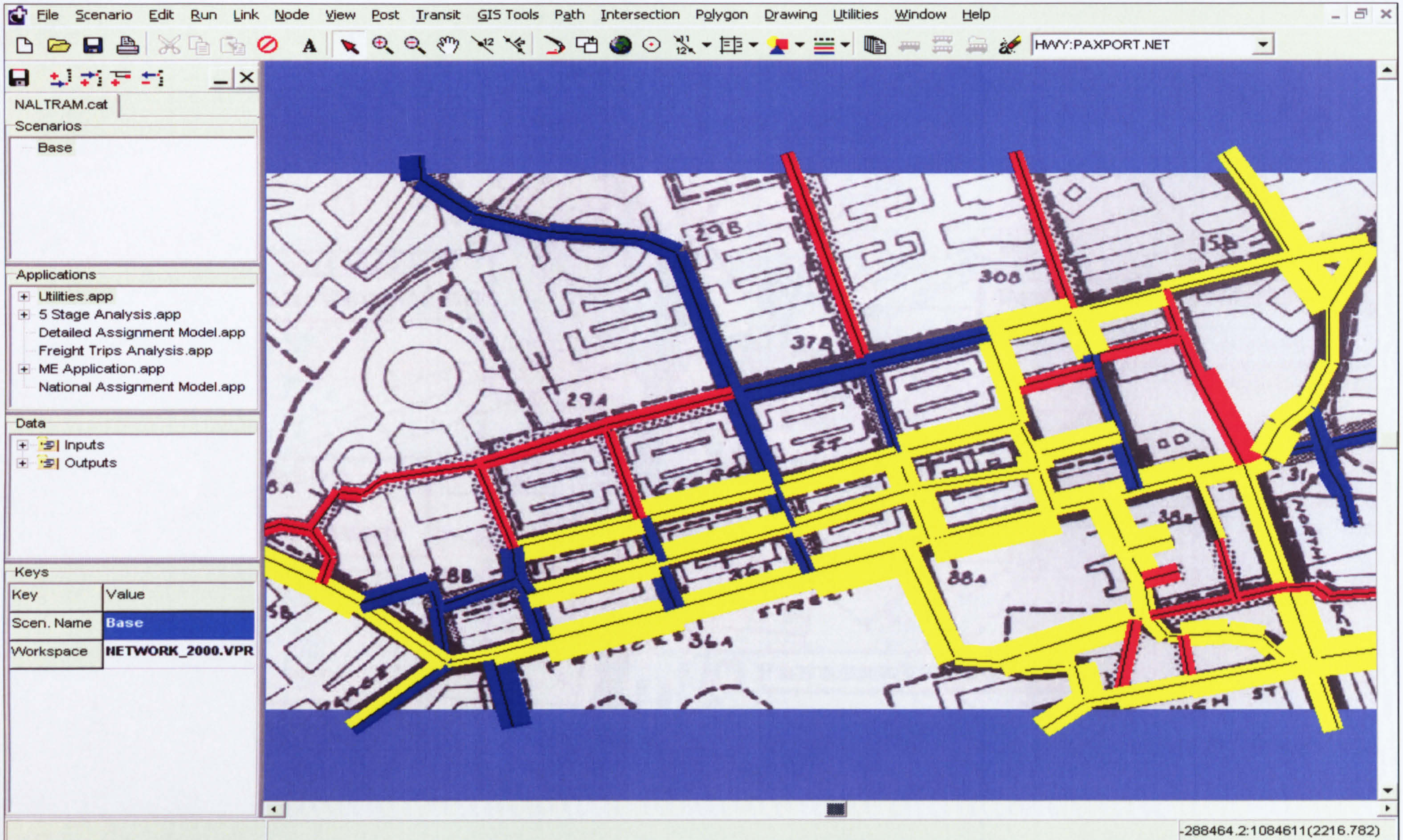


Edinburgh Pedestrian Study

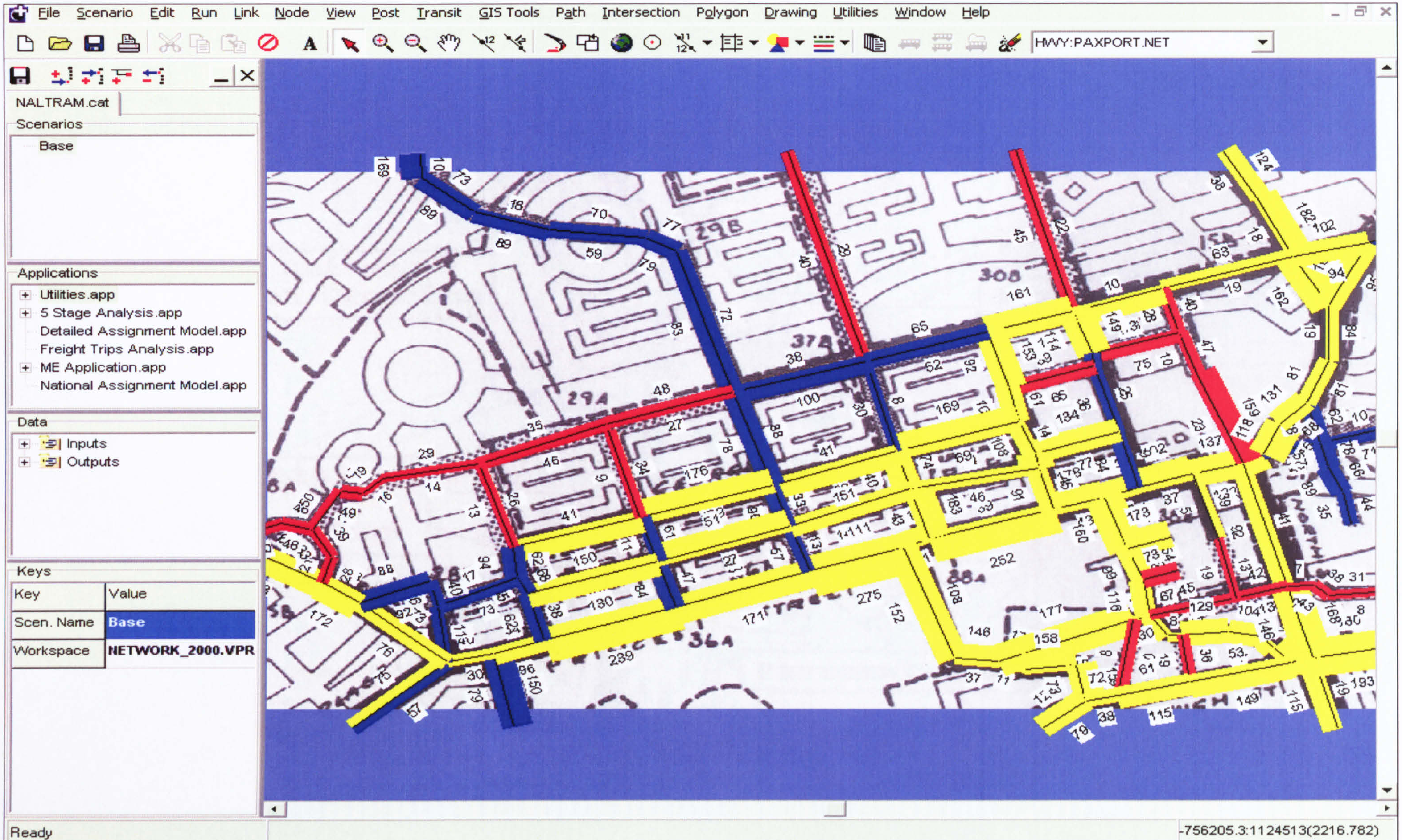
Example of Data Inputs for PEDROUTE Model

Appendix 4

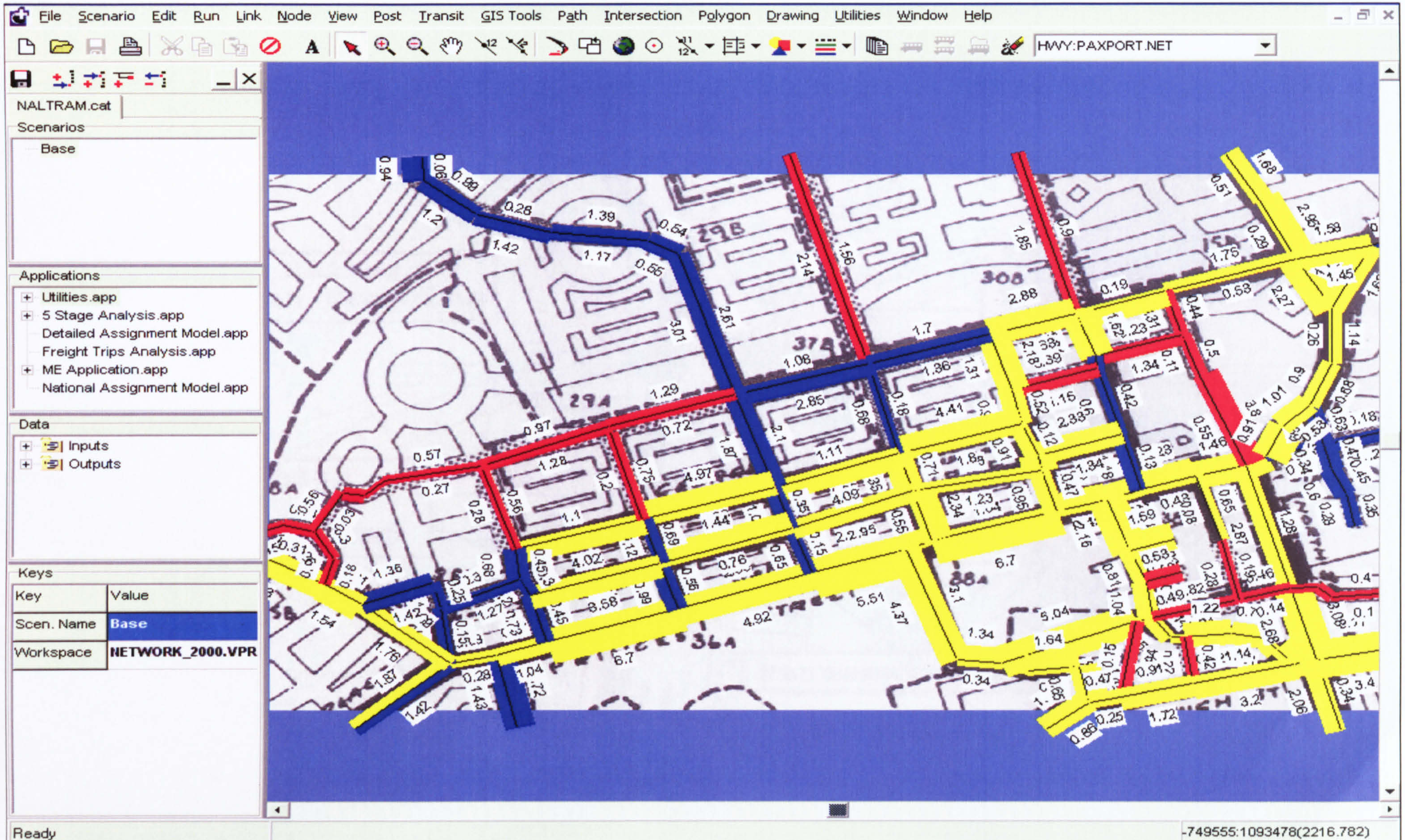
Figure A4.3



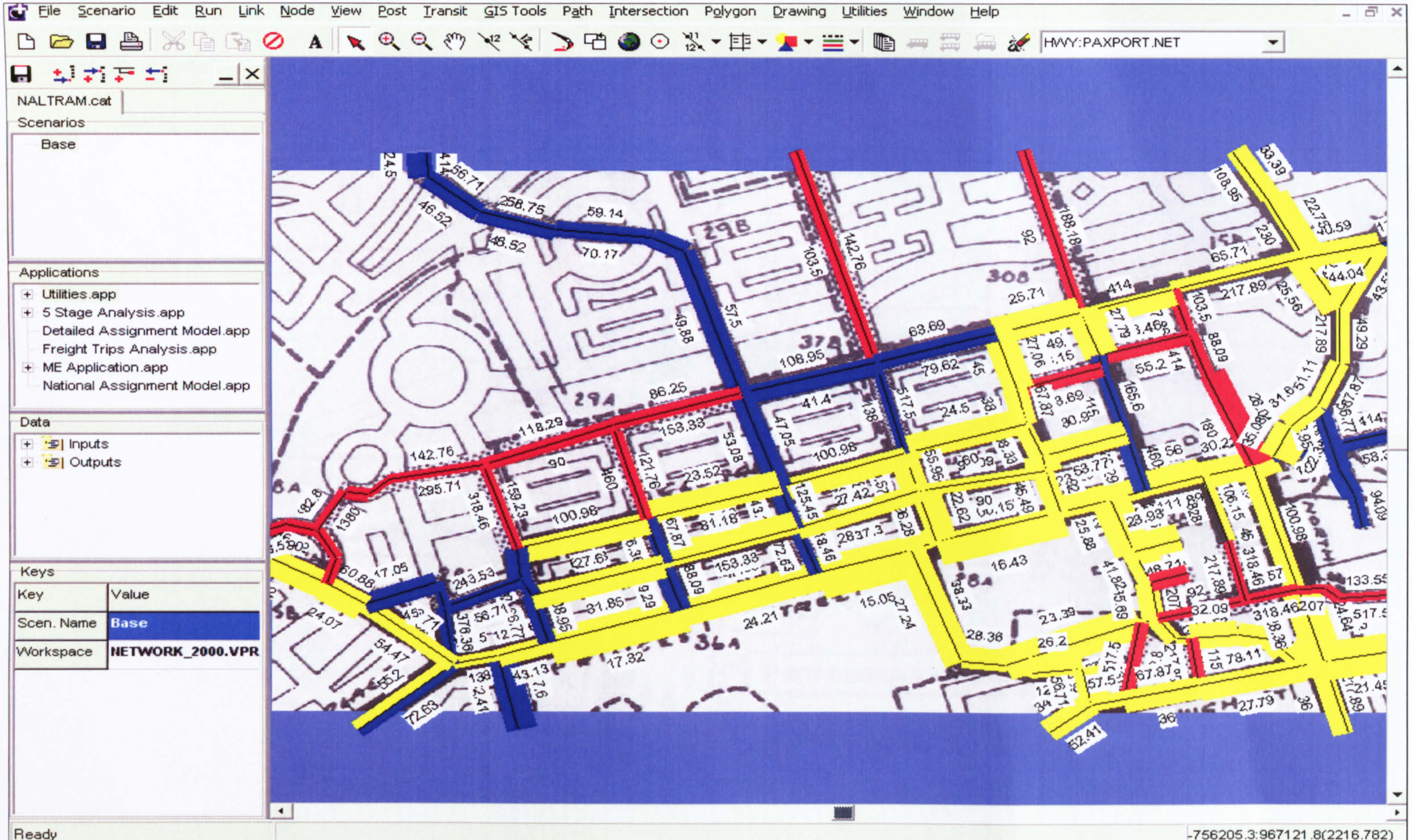
Edinburgh Pedestrian Study Example of Outputs from PEDROUTE Model	Appendix 4	Figure A4.4



Edinburgh Pedestrian Study Modelled Pedestrian Flows from PEDROUTE	Appendix 4	Figure A4.5



	Edinburgh Pedestrian Study Modelled Walking Times from PEDROUTE	Appendix 4	Figure A4.6



	Edinburgh Pedestrian Study Modelled Walking Speeds from PEDROUTE	Appendix 4	Figure A4.7