IMPACTS OF TRAFFIC CALMING MEASURES ON SPEEDS ON URBAN ROADS

by

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

To Nilson for his love, patience and encouragement.

To my family.

ABSTRACT

The main objective of this research was to improve the understanding of drivers' behaviour while negotiating traffic calming measures, through the study of the impacts of these measures on speeds.

A case study was conducted in the City of York focusing on speed humps (flat-topped and round-topped), speed cushions and chicanes implemented in sequence. Data collection was conducted at three calibration and three validation sites with vehicles' passing times simultaneously recorded at 16 points along the links. From these data a speed profile for each individual vehicle could be derived. The influence of various combinations of traffic calming measures on speeds of unimpeded cars and vans was evaluated through those speed profiles, and through acceleration profiles deduced from speed profiles.

The investigation of the hypotheses established from the analyses of speed and acceleration profiles gave insights into specific issues such as the consistency of crossing speeds, the additive effect of subsequent measures, the acceleration and deceleration rates associated with individual measures and travel times along calmed links. The knowledge acquired from these analyses was applied to the formulation of a speed profile model.

To describe drivers' behaviour along traffic calmed links an empirical model was developed using multiple regression analysis techniques based on data collected at the calibration sites. Speeds along calmed links were described as a function of the input speed, the type of measure and the distance between measures. The speed profile model was shown to be a good representation for the data from the calibration sites. It efficiently predicted speeds of unimpeded vehicles over a given combination of traffic calming measures in sequence. The validation process also indicated that the model provided a good representation of the observed profiles at these sites, with the exception of the prediction of the effects of the chicanes on speeds. This type of

measure was shown to produce diverse impacts on speeds which depended on the detailed design.

While the model is a useful design tool, recommendations have been made for further enhancement to it.

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LIST OF ABBREVIATIONS

Related to the surveyed sites:

FA = Fourth Avenue

FE = Foxwood Lane East

FW = Foxwood Lane West

GL = Gale Lane

LIV = Livingstone Street

TS = Townend Street

Related to variables:

d = distance

df = distance from the previous measure

dt = distance to the next measure

C = speed cushion

H = speed hump (round top)

T = speed table (flat topped)

Ch = chicane

V_n = speeds recorded at data point n (n = 16)

V1 = entry speed

tt = total travel time

SPM = speed profile model

CHAPTER 1

INTRODUCTION

1.1 Background

High speeds and excessive road traffic have long been a cause for concern due to the economic costs of accidents and environmental problems especially in sensitive areas. However, the expected growth in road traffic challenges the transportation planners with even more serious problems. Traffic calming has been seen as one of the possibilities to tackle such problems effectively. Traffic calming is the term that designates the application through traffic engineering of regulation and physical measures designed to control traffic speeds and encourage driving behaviour appropriate to the environment.

There are two ways of dealing with traffic calming: (i) in its wider sense with an overall policy involving the promotion of pedestrian, public and bicycle transportation in addition to the reduction of vehicle speed; or (ii) in a more restrictive sense reducing the dominance of vehicles in order to achieve a reduction in the level and severity of accidents, noise and air pollution and also the enhancement of the street environment for pedestrians.

Traffic calming has in many cases been adopted in its narrow sense, as a means of retrieving the primary purpose of roads which has been distorted by the speed and volume of traffic. Traffic calming has become commonplace in many urban areas firstly, as a result of government policy encouraging highway authorities to implement traffic calming schemes particularly aiming at the DoT's target of a reduction of road casualties by a third by the year 2000. Secondly, most local authorities consider traffic calming as an important element in their transport strategies. Finally, there is an increasing demand from residents for the introduction of traffic calming schemes in residential areas. Usually the adoption of traffic calming has resulted in more liveable streets with gains in environmental quality and road safety as a result of lower speeds and traffic reduction, as confirmed by reports on the assessment of various schemes.

Much has been written about the experience gained through the implementation of traffic calming schemes and most of the evaluations published so far are primarily concerned with the main objectives of traffic calming, which are to reduce overall speed and the number of accidents. Usually schemes have been assessed based solely on the overall reduction of vehicular speeds and the number of accidents. As a result, aspects equally important to the traffic engineer such as drivers' behaviour when negotiating specific traffic calming measures have been neglected. More recently studies have been dedicated to the assessment of the effect of individual traffic calming measures mostly concentrating on speed humps. Nevertheless, there is still a lack of information on the relative impact of different measures and in different combinations to effectively tackle the problems faced by traffic planners. The knowledge of the impact of traffic calming measures in different combinations would be a valuable contribution to the achievement of effective schemes which meet predetermined objectives.

1.2 Objectives

This thesis provides a detailed analysis of the influence of different combinations of traffic calming measures on the speed of unimpeded vehicles. This has been undertaken by evaluating the differences in speed profiles obtained from various combinations of traffic calming measures involving speed humps (flat-topped and round topped), speed cushions and chicanes implemented in sequence.

The emphasis throughout is on the formulation of an empirical model, based on data collected at six sites in the City of York, which explains the variations in speed profiles according to the type and position of measures within a sequence.

1.3 Thesis Structure

This thesis contains nine chapters, including the introduction and conclusions, Chapter 1 and 9 respectively. Two chapters are dedicated to literature review, two focus on the data collection and presentation, three concentrate on the data analysis and model development, and the last consists of the validation of the developed model.

Chapter 2 reviews the state of art of traffic calming, describing its origins, definitions, objectives, techniques, likely effects and impacts in practice. It presents the most important traffic calming evaluations carried out so far.

Chapter 3 concentrates on methods for surveying speed and travel time. Special emphasis is given to applications of technology in speed data collection mainly designed for the assessment of speed-reducing measures; to models describing vehicles' motion, and to the most important relationships contributing to the understanding of the effects of speed control devices.

The description of the data collection system and the conduct of the surveys at the three calibration and three validation sites in York is presented in Chapter 4. The chapter also gives emphasis to the subsequent phases of data selection and processing.

The next four chapters concentrate on the detailed analysis of the data collected.

Chapter 5 presents an initial data analysis and introduces the descriptive statistics calculated for the calibration sites as well as information on the distribution of the recorded speeds. It explores the speed profiles and acceleration profiles plotted for individual vehicles as tools to help viewing the data. Based on these analyses, the hypotheses to be investigated in this thesis are introduced.

Chapter 6 investigates the hypotheses previously established, searching for evidence on the consistency of the impacts of similar calming measures. Acceleration and deceleration rates and travel times in the studied links are also considered in this chapter. The knowledge acquired from these analyses is subsequently applied to the development and formulation of the speed profile model.

Chapter 7 accomplishes the objectives of this thesis through the development of an empirical model to predict the effects of certain types of traffic calming measures on speeds of unimpeded vehicles based on data collected at the three calibration sites in York. An assessment is also made of the use of the speed profile model to predict acceleration profiles.

Chapter 8 examines the validity of the speed profile model using additional data from the calibration sites and data collected at three validation sites. The model demonstrates its predictive capability except for one of the validation sites. An assessment of the application of the model is made for hypothetical traffic calming schemes.

Finally, the last chapter, Chapter 9, summarises the major conclusions of this work and puts forward recommendations and suggestions for further research.

CHAPTER 2

LITERATURE REVIEW

The aim of this chapter is to present a review of the main issues concerning traffic calming. The origins, objectives, types of measures and experiences of traffic calming have been reviewed with emphasis on the scheme evaluations carried out so far.

2.1 A Short History of Traffic Calming

Traffic calming seems to have its origins in traffic management measures introduced mainly in Germany and in the Netherlands. According to Hass-Klau et al (1992) Germany contributed to the development of traffic calming concepts through the increase in pedestrianisation in the town centres, the emancipation of residents' associations and an increase in public environmental awareness. In its turn, in the Netherlands the concept was developed by urban planners and traffic engineers "who realised that the well-being of people was influenced not only by housing but also by the surrounding streets" (Hass-Klau, 1990).

Hass-Klau (1992) wrote that the central European traffic calming concept has always been vague. As a result of that, its origin is difficult to trace. But according to the same author (1990a) its policy could be seen as having developed from three related roots:

- the idea of **environmental areas**, a phrase which was made popular by Colin Buchanan in "Traffic in Towns" in 1963. The first examples of what today would be called traffic calming measures were implemented in environmental areas in many British towns in the late 1960s;

- the new design denominated by Dutch planners as **woonerf** (residential yards) in which the focus is on avoiding the traditional separation between carriageway and pavement. On the surface created, all road users were mixed and had equal rights.

The maximum motor vehicle speed was restricted to walking pace. It has the functions of a residence, meeting place, playground and walking area. This public area has the additional function of carrying traffic, but no function for through traffic; and

- **pedestrianisation** schemes which generally mean the closure of existing streets to traffic followed by paving, tree planting and street furniture. In the first schemes introduced in city centre streets cyclists were not allowed and service vehicles had only rear access. More recently pedestrianisation has been extended to local shopping streets and both there and in city centres various uses and functions such as service vehicles, cyclists and public transport have been mixed with pedestrians.

As Hass-Klau put it "the combination of these three ideas had a considerable impact on how traffic calming has been understood and implemented in Europe". Some of those ideas, especially those concerning Woonerf have suffered some adaptations and changes due to high costs of implementation. To quote Hass-Klau et al (1992) again, "the 30 km/h speed-limit zones, first introduced in the Netherlands in 1983, were seen as a cheaper and more effective option than woonerven, because large areas could be treated for the same amount of money and with similar effects".

When comparing what has been written under the name of environmental traffic management by many authors (e.g. Keller (1986), Bowers (1986), Monheim R (1986), Nielsen and Rassen (1986), Monheim H (1986), and Russell (1988)), the relationship to traffic calming objectives and methods is easily noticeable. The first indication of environmental traffic management appears to be through the implementation of pedestrianised areas. However, the development of this idea followed different streams throughout many central European countries.

In Britain, environmental traffic management has its origins in the report 'Traffic in Towns' and it is described as a technique to protect the environment against adverse effects of motor traffic by means of applying traffic restraint measures. Although concepts were developed earlier in Britain, implementation was delayed. The continental experience in traffic calming in residential areas, city centres and more recently on main roads is much more extensive than the British experience. For example, Hass-Klau et al (1992) commented that "a large project on traffic calming in British town centres started 12 years later than the German equivalent and 16 years behind the Dutch version". However, the last five years have seen the extensive adoption of traffic calming in Britain.

The woonerf, originated in 1975 in the Netherlands, has been widely applied to Dutch towns and cities and has been the most celebrated Dutch contribution to urban environmental traffic management. Shopping areas and villages have also been treated with traffic restraint measures and woonerf rules were expected to be extended to include shopping areas and villages (Kraay, 1986).

In Germany, the conceptual and practical development of environmental traffic management started firstly with the development of pedestrianisation schemes on a very large scale. Residents' organisations were very important in strengthening the awareness of the need to protect pedestrians and residents from increasing motor traffic, in fighting against new road proposals and also in demanding the reduction of traffic flows in residential areas. Residents' associations were also backed up by the growing publicity on environmental issues. In view of this, new solutions for residential areas were sought and residential street improvements became part of the whole process of urban renewal to pursue 'liveable streets', giving equal rights to pedestrians, children, cyclists and public transport users. To this end, traffic management restraint measures have been applied to residential areas using a variety of different treatments (Hass-Klau, 1990). The German version of environmental traffic management could be seen as a mixture of the theoretical British concept of environmental areas and the Dutch woonerfs (Hass-Klau, 1986a).

Environmental traffic management in Denmark may be said to have begun with the Dutch woonerf. However, the term 'environmental traffic management' does not precisely describe the variety of purposes served by traffic management schemes and traffic restraint measures applied to a wide range of situations in Denmark. 'Rest and play areas' subjected to regulations similar to woonerf and the Danish '30 km/h quiet areas' with a minimum of regulations and a more realistic speed limit, are among the types of environmental traffic restraint measures or 'traffic integration'. Other measures include safe routes to school, major road schemes in urban areas, village schemes, speed reduction measures on bus routes and area-wide schemes (Russell, 1988).

2.2 Definitions and Objectives

Since about 1976, the word 'verkehrsberuhigung' or 'traffic calming' has become the accepted expression, although there are great variations in its meaning (Hass-Klau, 1990). Traffic calming was seen as a reaction against an extensive road building programme in Germany. Traffic calming was not clearly defined, thus allowing different interpretations varying from alternative urban transport policies to simple engineering measures to reduce vehicle speed in residential areas. As mentioned earlier, the theoretical justification came from Britain through Buchanan's environmental areas concept, whereas the practical approach came from the Netherlands through woonerven. During the earlier 1980s transport experts argued about the exact definition of traffic calming but no agreement has ever been reached (Hass-Klau, 1990).

Traffic Calming may be defined in a wider sense and in a narrow one. The former envisages an overall transport policy which includes, "apart from a reduction of the average motor vehicle speed in built-up areas, a strong promotion of pedestrian, public and bicycle transport" (Hass-Klau, 1990a). The latter may be considered as a policy to reduce vehicle speeds in built-up areas and hence the environmental impact of those vehicles.

Regarding traffic calming in a narrow sense its main objectives fall into three categories as follows:

- to reduce the number and severity of accidents;
- to reduce noise and air pollution; and
- to enhance the street environment for pedestrians by reducing the car's dominance.

Traffic calming definitions are strongly related to their objectives and in some cases objectives and definition merge as can be seen in the following definitions:

> "traffic calming is defined as an adaptation of the volume, speed and behaviour of traffic to the primary functions of the streets through which it passes, rather than to adapt streets to the unbridled demands of motor vehicles" (Devon County Council, 1991).
>
> "traffic calming may be defined as the attempt to achieve calm, safe and environmentally improved conditions in streets" (Pharoah and Russell, 1989).

In the second the objective is clearly incorporated into the definition.

In spite of some differences in definitions, they are all based on the main principle of accommodating traffic in an environmentally acceptable way. McCluskey (1992) justifies traffic calming as a method to curb the impact of cars in town centres and housing developments, and among traffic calming aims he considers the reduction of traffic volume in selected areas, the reduction of vehicle speeds in such areas and pedestrianisation in certain circumstances.

According to a group of Australian practitioners, the many apparently divergent definitions of traffic calming were reconciled and three levels of traffic calming were identified and reported by Brindle (1992):

> Level I - actions restricted to the local level (residential) to restrain traffic speed and reduce traffic impacts;
>
> Level II - actions extended to an intermediate level (corridor, through routes);
>
> Level III - actions at the macro level to lessen traffic levels and impacts city-wide.

Level III brings traffic calming into the area of urban transport policy whereas the first level focuses on the most common form of traffic calming action which is called in Australia 'Local Area Traffic Management' or 'Residential Street Management'. This separation into levels is just another interpretation of the wider and narrower definitions of traffic calming.

The British approach to traffic calming has mostly been pursued in the narrow sense, that is, in the absence of co-ordination between planning and transport. Hass-Klau (1990) stated that "it has been seen purely as a traffic engineering approach and not as part of improving the urban environment".

This is consistent with Collins' views of the Continental experience, which "indicates that the countries which have made most progress with traffic calming regard it as part of the wider context of a coherent transport policy".

A focus for wider environmental improvements is suggested by Ellis-King (1993) as a joint approach between the roles of the engineer and landscape architect/urban designer in order to achieve a balance in terms of traffic management, safety, visual quality and amenity value of the treated area. Traffic calming should be seen as an opportunity for environmental improvement in its broadest sense while tackling traffic management and safety issues.

Traffic calming concepts and techniques have been developed and enriched since the early practical and theoretical ideas, and according to Collins (1990) "traffic calming employs a variety of techniques ranging from simple traffic management to comprehensive highway reconstruction".

Although definitions may differ in interpretation of what traffic calming is, Collins referring to its narrow objective, observed that "there is a clear implication of what it is not. Traffic calming does not mean positively excluding extraneous traffic, but moderating its behaviour. Indeed, it is an approach which is adopted because extraneous traffic cannot be excluded" (Collins, 1990). However, the issue of extraneous traffic can possibly be dealt with by restrictive measures, which are related to the wider objectives, as mentioned in the next section.

2.3 Traffic Calming Measures

There is a wide range of traffic calming measures designed to achieve both narrow and wide traffic calming objectives. In this connection, traffic calming measures can be split into two broad categories:

a) specific traffic calming measures designed primarily to reduce vehicle speeds and to create an environment conducive to calm driving. This group comprises a range of measures designed to complement each other in terms of speed reduction and environmental enhancement, and is the focus of this study; and

b) restrictive measures against the motor vehicle in accordance with the needs of the built-up area. Such measures are related to the wide traffic calming objective and among this group can be considered:

road pricing;

parking restrictions and road closings;

HGV control and routeing;

car taxation and company car tax allowances; and

land-use policies (to reduce the need for motor vehicle trips).

These restrictive measures together with promotion of public transport could form part of an overall transport policy which fulfils what has been defined by Hass-Klau as a wider traffic calming objective. They are outside the terms of reference of this present study.

With regard to traffic calming measures of group (a), general views on issues such as effectiveness, objectives, positive and negative factors are shared by Harvey (1992), Hass-Klau et al (1992), Devon County Council (1991), and DoT (1993). They vary in the depth of each author's approach to the subject, the categorisation of measures and their nomenclature.

Devon County Council has categorised group (a) measures in two subgroups, namely (i) speed reduction measures and (ii) supporting environmental and safety measures. However, this categorisation cannot be applied very strictly as, for instance, in most cases the application of speed reduction measures helps to meet environmental and safety enhancement. For this presentation of current traffic calming techniques, measures have been grouped into five areas namely: vertical deflections, horizontal deflections, carriageway constriction, traffic management measures and speed limits. A brief description of measures is presented in the next section as a compilation of relevant information acquired from the references mentioned above.

2.3.1 Vertical Deflections

There are currently some different techniques available to introduce vertical deflections in the carriageway. They may be constructed using a variety of materials, and this change in materials helps in terms of visibility as well as the speed reduction effect. Vertical shifts do not contribute to environmental enhancement and may be regarded as unsightly but they are most effective in terms of speed reduction (Devon County Council, 1991). The most usual types are:

Road Hump

A road hump is a raised portion of the carriageway laid at right angles to the direction of traffic. It is the most commonly used traffic calming measure in Britain (Hass-Klau et al, 1992). The rounded and flat topped humps are the most common and the latter can assist pedestrian crossing movements (Harvey, 1992). They are usually built from kerb-to-kerb or tapered off at each end for drainage purposes (Devon County Council, 1991).

Speed Cushion

Speed cushions are a raised portion of the carriageway with a flat top extending over part of the carriageway width. Still having the same positive speed reducing effect as road humps, they avoid the main disadvantage for buses and ambulances. The design allows vehicles with wider axle-width than cars to remain relatively unaffected. However, depending on the design, vehicles with double-rear wheels may be affected by speed cushions. Two wheelers are not affected because sufficient carriageway on both sides of the speed cushion is left for them to pass unhindered. As a result, high speed motorcycles could still cause problems as the vertical shift can be avoided (Devon County Council, 1991).

Plateau

A plateau is defined as a section of the carriageway from kerb-to-kerb raised via ramps to footway height covering the whole of a junction or extended over a longer length of road than humps when implemented on links. It is also termed a speed table and the surface should be of a different material from the carriageway and footways. Plateaux are more suitable than road humps when the measures are installed on bus routes (Harvey, 1992).

Rumble Devices

Rumble devices - rumble strips and jiggle bars - are small raised areas across the carriageway which are designed primarily to alert drivers and encourage them to slow down for particular hazards. The devices have the effect of sending severe vibrations through the vehicle to the driver and passengers. Care should be taken in the use of rumble devices due to the increase in the noise level. Jiggle bars have been found to be ineffective in reducing vehicle speeds. On the other hand, speeds may increase as drivers discover that the effect can be reduced when negotiating the devices at higher speeds (Harvey, 1992; Webster and Layfield, 1993).

2.3.2 Horizontal Deflections

Horizontal deflections or lateral shifts in the carriageway aim to reduce traffic speeds and thus improve safety, to rearrange street space for pedestrians by extending footways and providing sheltered parking and to interrupt long views. Horizontal shifts are less effective than the vertical ones in achieving reductions in speed, however their effectiveness increases when used in combination with a vertical deflection (Harvey, 1992).

Pinch Points

Pinch points reduce the carriageway width on opposite sides at a specific part of the road. The design can provide carriageway width where two cars can pass each other at low speed but one car and a large vehicle would have difficulties in passing. Another usual approach is to allow one vehicle at a time by reducing the carriageway width even more. In this connection the form and shapes of pinch points may vary considerably (Hass-Klau et al, 1992). The effectiveness of such measures is related to the severity of their design and also to their combination with other traffic calming measures. The main problem is the limited effectiveness in reducing the average speed to 20 mph or less and also the small effect on two wheelers.

Chicanes

Chicanes are different forms of pinch points implemented on alternating sides. The number of design types appears to be almost unlimited and the differences between chicanes and pinch points are sometimes indistinct (Hass-Klau et al, 1992). The horizontal shift must be sufficiently severe to enforce the physical turn, otherwise the impact on speed reducing may be minor if the chicane has to allow for the passage of large vehicles as the wider carriageway will encourage drivers of narrower vehicles to travel at higher speeds. Narrow width is only recommended where traffic flow is very low. Therefore, it is difficult to achieve good speed reduction while providing access for larger vehicles (Devon County Council, 1991). The effectiveness of chicanes is similar to pinch points. Chicanes can generate interesting street design and the footway extensions may be used as flower beds to enhance the environment and at the same time its adoption may avoid the need for vertical shifts which are often considered unsightly. However, chicanes can look unattractive if cheaply designed (Hass-Klau et al, 1992).

2.3.3 Carriageway Constrictions

Carriageway constrictions are an important feature of multi-objective traffic calming design, but need to be combined with other measures for effective speed reduction (Devon County Council, 1991). The main difference between this measure and pinch points is related to the extension of the narrowing which in this case is implemented along the whole stretch of road to be traffic calmed (Hass-Klau et al, 1992). Carriageway narrowing can be achieved by road markings or physical measures in the form of widening the footway, parking provision, central islands (traffic islands or pedestrian refuge), cycle and bus lanes, and planting trees which can be seen as a supporting measure.

With regard to hatched road markings Hass-Klau et al (1992) are doubtful whether road markings can be called a traffic calming measure because their speed-reducing effect is questionable. Central islands are also considered to have a limited effect on reducing speeds and, as with any other carriageway constriction measure, their effectiveness in achieving a significant speed reduction depends on their combination with another more restrictive measure such as chicanes or vertical shifts. Nevertheless, central islands provide useful pedestrian refuges.

2.3.4 Other Traffic Management and Traffic Calming Measures

The distinction between traffic calming measures and traffic management measures is not very clear as the borderline appears to be very subtle. The distinction may be made according to the objective of the scheme implementation. Measures can be applied on links and at junctions. Traffic signs, planting (trees and greenery) and parking provision are supporting traffic management measures that can achieve traffic calming goals if they are used in conjunction to other measures. Among the most common measures are:

Road Closure

Road closure is not a very popular measure as it restricts accessibility and the choice of routes available for local access traffic, but it can be very effective in removing through traffic. However, the effects on parallel streets through traffic redistribution can be a problem for the residents living there. The adoption of many road closures in an area may increase journey times resulting in delays for essential services such as emergency vehicles.

Roundabouts

Roundabouts are used to reduce speeds, smooth the traffic flow and reduce vehicle conflicts. The design of conventional roundabouts tends to limit their use, therefore mini roundabouts are often used within residential areas (Devon County Council, 1991). Roundabouts have a negative impact on cyclists because of the danger from conflicting movements. They are also a problem for pedestrians since they are difficult to negotiate (Hass-Klau et al, 1992).

Changed Road Surface

Surface changes in type, colour and location aim to distinguish between different surface functions, to improve street appearance, and to reinforce speed reducing measures. This can be achieved by using different materials and/or colours, but the materials should be chosen according to the existing street character. Change of road surface in the form of strips achieves a speed reduction effect especially when combined with vertical shifts or pinch points. Covering the whole carriageway is mainly used to improve the urban environment and it is primarily implemented in shopping and historic town centre streets. A negative factor is the noise generated from rough surfaces. Cyclists and pedestrians may experience discomfort and hazard due to rough surfaces (Devon County Council, 1991).

Entrance Treatment

Entrance treatments or gateways are especially designed to mark the beginning and end of areas where different rules for drivers apply. For instance the entrance to a traffic calmed area requires special attention to indicate to drivers the start of a speed limit zone. The design of an entry treatment can incorporate a variety of features such as: build-outs and pinch points, traffic islands, changes in surface texture or colour, vertical deflections of the carriageway, bollards and planting, tactile paving, signing, vertical design elements e.g. posts, pillars, walls, fences (DoT, 1991a).

Shared Space

Shared space is defined as abandoning the traditional division between carriageway and pavement to allow pedestrians freedom of movement within the street while vehicle speed is restricted to walking pace. It was introduced in the Netherlands as woonerven. It is suitable for local streets with no through traffic and low traffic flows. The design needs to include planting, paving, street furniture and other elements to create safe and convenient conditions for all road users. Shared space can be very effective in reducing vehicle speeds but needs a careful design to curb vehicle speeds otherwise it may give a false feeling of security for pedestrians (Hass-Klau et al, 1992).

2.3.5 Speed Limits

This topic deals with different versions of speed limit areas introduced in the Continent and in Britain.

Tempo 30 Zones

Tempo 30-zones are one of three traffic law instruments of environmental traffic management in Germany. They include the following characteristics: all vehicles allowed, maximum speed 30 km/h, parking allowed, vehicles having priority on the roadway, only few street layout changes, and area-wide application in residential and central areas.

Normally Tempo 30 is connected with supporting measures of traffic control and road construction and street design. The former are usually implemented in such schemes and involve priority to the right at junctions and the elimination of traffic signs and road markings. Measures of road construction and street design are less usual than traffic control measures (Schleicher-Jester, 1989).

30 Km/h Zones in The Netherlands

In the Netherlands, the 30 km/h zone regulation is in itself a legal measure. However, it has become evident that the simple use of speed limit traffic signs cannot achieve a 30 km/h limit if the area's nature and layout are not conducive to this way of driving. Therefore, a large number of speed restricting engineering measures have been designed over the years. The desired speed limit effect is obtained by combining and/or repeating the following four types of engineering measures that show an increasing level of coercion:

informative: the road users are alerted to the fact that a particular kind of behaviour is expected from them;

suggestive: the road users are subconsciously urged to adopt a certain kind of behaviour;

persuasive: the road user is clearly persuaded to behave in a certain manner; and

obstructive: specific traffic behaviour is physically forced on the driver (Vis et al, 1992).

Rest and Play Areas in Denmark

Rest and play areas are subject to regulations similar to those in the Netherlands for woonerven. Drivers must give way to pedestrians, stopping and waiting for the area to clear if necessary. Physical speed inhibiting measures must be frequent, with a legal maximum of 50 metres between them, and should be sufficient to obtain compliance with the speed limit of 15 km/h. Parking is forbidden except in marked places (Russell, 1988).

The 30 km/h Streets in Denmark

The 30 km/h street, a second type of 'living area', was created to produce environmental improvements for residents and to provide better conditions for vulnerable road users in addition to 15 km/h streets. This traffic calming scheme is achieved by introducing a speed limit of 30 km/h and some, but fewer restrictions concerning physical measures. The flexibility of their concept and the freedom from regulations and standards have produced a large variety of schemes, and became popular and most frequent in residential areas (Russell, 1988).

20 mph Speed Limit Zones in Britain

According to British regulations, a 20 mph speed limit zone cannot be introduced without the supporting physical measures to enforce that speed limit. Zone signs must be erected at every entrance to the zone. At exits, a zone sign indicating the speed limit of the adjoining road must be displayed. The erection of the zone sign will help to establish a gateway effect. However, Hass-Klau et al (1992) are aware that speed limit signs by themselves have little or no effect. Therefore, a change in the surface texture of the carriageway and/or narrowing the carriageway combined to a speed hump can ensure a reduction of vehicle speeds at the entry point. Within the zone a combination of traffic calming measures is recommended to ensure that speed is kept within the desired level (DoT, 1991a and 1994).

2.3.6 General Comments

The Department of Transport recommends the use of a range of traffic calming measures rather than relying on one type of device. Furthermore, it also suggests the diversification of material and colour of the road surface as well as the adoption of planting, following the features of the woonerf. However, the most usual practice has been the adoption of road humps as a cheap substitute for traffic calming particularly as a result of a great demand from the public to implement traffic calming schemes and severe budget constraints.

In a review of the 20 mph speed zones, which forms part of a research programme conducted by TRL, Hodge (1992) noted what seems to be a lack of variety in the type of measures implemented in the schemes under analysis since flat-topped tables were the most usual measure.

There is no doubt about the effectiveness of road humps in reducing speeds, but quoting Hass-Klau and Nold (1993) again, "road humps should only be seen as one choice among many to reduce speed and they should also be used to improve the street environment".

It is noteworthy to stress that the best results in terms of reducing the adverse effects of road traffic and creating a calm way of driving are achieved when those measures are implemented in combination (e.g. Devon County Council (1991), Doldissen and Draeger (1990), Pharoah and Russell (1989), Hodge (1992), Schleicher-Jester (1989), and Bowers (1986)).

2.4 Likely Effects of Traffic Calming Schemes

Much has been written about the continental experience stressing the advantages achieved in calmed streets. Undoubtedly those schemes have resulted in liveable streets with gains in environmental quality and road safety as a result of lower speeds and traffic reduction in residential areas. There are a number of both desired and undesired effects. Literature about traffic calming seems to be emphasising only its positive aspects (desired effects) without discussing more properly other important issues such as unexpected effects.

Undesired impacts have been listed under different headings to ease presentation. It should be noted that some of the impacts considered in this section have not been quantified and sometimes may reflect commonly held but unsubstantiated opinions.

2.4.1 Traffic Redistribution

Strategies for traffic flow reduction may provoke the displacement of traffic (intentionally or not) to alternative routes. Displaced traffic may generate negative effects when it is directed towards unsuitable roads. Traffic being transferred to alternative adjacent routes after the implementation of traffic calming schemes has been observed by Monheim R, (1986), Appleyard (1981), McNamara (1983), TEST (1989), Baguley (1981), Kraay (1986), Russell (1988), and Devon County Council (1991). In evaluating speed control humps, Sumner and Baguley (1979) noted that the level of traffic flow diversion was related to the availability of alternative routes.

Windle and Mackie (1992) carried out a survey on public acceptability of traffic calming schemes. They have reported that nearly half of all car drivers living in the four study areas said that they had changed the routes they took as a result of the scheme in their area in order to avoid the humps in the road. Avoiding traffic calmed routes usually diverts traffic onto other residential streets, thus increasing traffic volume. Windle and Mackie (1992) also stated that "there is a clear perception (among respondents) that other drivers have also changed their routes as a result of the introduction of these schemes, in overall terms 58% said that this was the case".

Traffic calming may also lead to a reduction in overall traffic levels. Evidence from Haringey (in London) suggest that many vehicles have 'evaporated' according to preliminary assessments (Devon County Council, 1991). However this issue needs more research. Evidence has also been found on overall traffic reduction as a result of modal switching as mentioned in section 2.4.8.

2.4.2 Land-use

According to Monheim (1986) "increased business in pedestrian areas also has its disadvantages: commercial rents rise out of all proportion and can no longer be met by weaker retail businesses and by non-commercial tenants. This increases the general tendency for the spread of chain stores and the resultant loss of the town's individuality."

Hass-Klau, (1990) commenting on the findings of Monheim, pointed out the loss of population in the city centres and in areas close by, largely caused by the takeover by other land-use functions, such as retailing and office developments.

2.4.3 Congestion

In mentioning the benefits of TRL project improvements for West Reading, Hass-Klau (1986) argues that the narrowing of residential roads appears to be ineffective, and in general the improvements are questionable once the area appears even more congested than before .

2.4.4 Trading

At first the most fundamental attacks on traffic calming were launched by retailing organisations (Hass-Klau, 1990). The existing problems could be overcome with the cooperation of retailers and Local Authorities. However, the impacts have proved to be positive and an exceptional rise in turnover in the retail trade was verified as a result of pedestrianised streets (Monheim R, 1986, Pharoah, 1992 and TEST, 1989). Moreover, the fears of loss of trade are usually proved to the contrary in calmed areas (Pharoah and Russell, 1989).

Analysing the impact of pedestrianisation and traffic calming on retailing, Hass-Klau (1993) states that the higher rental values that typically result from pedestrianisation benefit the landlord rather than the shop owner as also observed by Monheim.

2.4.5 Journey Times

Increase in journey times when travelling through calmed areas is a real concern for many road users especially for emergency services such as ambulances and the fire brigade. The introduction of traffic management schemes involving redistribution of traffic can affect journey times as reported by Mackie et al (1988). McDonald (1983), studying the effects of speed humps, has mentioned that travel times have been increased due to the installation of the speed reducing devices. Increases in travel times were also verified by Sumner and Baguley (1979) and Baguley (1981) when assessing the effects after the implementation of speed control humps.

2.4.6 Accessibility

Restrictive traffic calming measures and traffic management measures in isolation or combined may result in restrictions to the accessibility within local areas. Restrictions in residential areas may increase travel distances (Ward and Allsop, 1982; Mackie et al, 1990).

2.4.7 Safety

In spite of traffic calming schemes being designed to improve safety in the area by reducing traffic volume and vehicle speed, schemes may produce negative impacts with regard to accidents being displaced to other roads as a consequence of diverted traffic (Russell, 1988; Ward and Allsop, 1982). This view is consistent with the results of a study of accident changes due to the implementation of speed humps which has suggested an increase in casualties in the surrounding roads (Sumner and Baguley, 1979).

Russell's approach suggests that reductions in accidents have been achieved in 30 km/h areas. He raises the issue of traffic and consequently accidents being displaced to other routes. This could mean no gains in road safety if the risk compensation mechanism operates (Adams, 1985).

In terms of road users' safety perception McNamara (1983) observed a false sense of security afforded by speed humps. Conversely, pedestrians, especially those with visual handicap, can feel insecure in shared space schemes because of the absence of kerbs (Devon County Council, 1991). The technique of shared spaces may provoke conflicts between cyclists and pedestrians as well as between pedestrians and buses. The problem seems to be more serious for elderly people and children when competing for the same space with cyclists and motor vehicles.

2.4.8 Mode

Some German cities have experienced a considerable increase in the use of public transport and bicycles and a perceptible reduction in car traffic in some areas (Monheim H, 1986).

In discussing modal split due to traffic calming schemes, Tolley (1990) wrote that in Buxtehude "a sharp rise in bicycle use is likely to be a result of the greatly increased opportunities for cycling, rather than of transfer from other modes." "...there is no evidence yet of transfer to public transport". About the likely disappointment which might result from failure to achieve expected modal switching, Tolley argued that "perhaps this reflects over-ambitious goals rather than failure of projects".

According to Monheim's approach, much traffic disappears from treated roads but does not reappear elsewhere. This may be because calming has encouraged drivers to change to public transport or to the green modes - walking and cycling. (Tolley, 1990). However, this point of view is inconsistent with the assessments of schemes implemented in Buxtehude, which shows that there is unlikely to have been a significant change of modes, as mentioned earlier.

According to Tolley's approach, "in simple terms, building roads generates traffic, removing them degenerates traffic. Evidence from city-wide calming in places like Odense and Freiburg is beginning to appear in the form of clear indications of the reduction in car use that follows environmental traffic management measures." In discussing road building, Pharoah (1992) wrote that "one of the most effective ways of avoiding traffic growth is simply not to provide for it".

2.5 Scheme Evaluations Carried Out So Far

Since traffic calming on the Continent has been more extensive than in Britain, the evaluations of implemented schemes also reflect that situation, even though literature on these evaluations is often scarce. Among the reviewed literature concerning scheme evaluation, two categories of publications were broadly identified, namely (i) on comprehensive schemes and (ii) on individual measures.

2.5.1 Evaluations of Comprehensive Schemes

Publications on environmental traffic management schemes usually present an overall scheme assessment mainly in terms of speed reduction and gains in road safety (accident reduction). The great majority of references are very general in relation to quantitative assessment of other related issues. In addition to this, there is a lack of information about methodology and field measurements. This situation can be illustrated by the following references Hass-Klau (1986) and (1986a), Nielsen and Rassen (1986), Kraay (1986), Schlabbach (1991), and Just (1992).

Some of these comprehensive scheme evaluations are presented in Table 2.1 to facilitate the comparison of the depth of the analysis. It is notable that traffic calming scheme assessments have assessed success or failure of the scheme as a whole. Evaluation is rarely confined to an individual measure such as a hump or a chicane (Pharoah and Russell, 1989).

In addition to the examples in Table 2.1, the nation-wide survey on traffic calming undertaken by Environmental & Transport Planning (Hass-Klau et al, 1992) documents that most of the implemented schemes had been successful, as reported by local authorities. In general, the schemes' results are presented as reductions in speed, traffic flow and number of accidents in the treated area. Still referring to specific reports presented by local authorities on the development and monitoring of traffic calming schemes, Harrison's (1992) report about Devon's experience, confirmed that hump schemes, either flat-top or round-top, are most effective in reducing speeds in residential areas.

Pharoah and Russell (1989) discussed evaluations carried out into the effects of traffic calming schemes on different issues such as speed, traffic volumes, accidents, noise, pollution and parking. The report is a compilation of the most important findings on traffic calming schemes implemented in Germany, Denmark and The Netherlands. Nevertheless, there is a lack of mention of the methodologies applied for undertaking those evaluations.

Evaluations have usually been undertaken at a disaggregated level, and specific criteria established in order to measure the effects of a scheme in relation to component objectives (Pharoah and Russell, 1989). Similar lack of information can be found among the 33 traffic calming scheme examples presented by Devon County Council (1991): only six were assessed by measurements of before and after speed and volumes, moreover most of the examples seem to have been assessed by observation methods rather than quantitative ones.

Table 2.1: Summary of some comprehensive scheme evaluations

SCHEME	Environmental Traffic Management in German towns	Tempo-30 Germany	Tempo-30 Germany	Area-wide Urban Road Safety - UK	30 km/h Zones The Netherlands
MEASUREMENT	before/after	before/after control area	before/after	before/after control areas	before/after control area
AUTHOR	Döldissen (1988)	Krause (1986)	Schleicher-Jester (1989)	Mackie, Ward and Walker (1990)	Vis, Dijkstra and Slop (1992)
IMPACTS:					
SPEEDS	reductions of up to 20km/h	mean reduced from 47 km/h to 34 km/h	after average speed about 30 km/h	small effect on mean speeds, large effect for 85th percentile	85th %ile about 30 km/h (for humps, road narrowing, barricades and gateways)
JOURNEY TIME	-	increased by 11%	nearly the same as before	no overall increase	-
TRAFFIC FLOW	-	-	diversion lower than more extensive ETM measures	diversion onto more suitable roads according to objectives	reduction by 5% to 30% of through traffic
ROAD SAFETY	fatal injuries down by 57% severe down by 45% light down by 40%	not very successful	accident frequency does not decrease in all schemes, severity does	reduction of 13% in accidents; slight injury reduced more than fatal and serious	accidents with injury down by 25%; all accidents down by 5%
NOISE LEVEL	reduced by 5 to 6 dB(A)	reduced by 7 to 11dB(A)	reduced by 3dB(A)	-	-
EMISSIONS	reduction 20% CO and 30% NOx	reduction 20% CO and 6% NOx	reduction in exhaust fumes	-	-

Wheeler (1992) reported in a TRL Working Paper the summary of measures implemented or proposed to reduce speed of traffic through villages in the UK and in other countries (Denmark, France, Germany). Assessments of UK schemes are only related to speed measurements and traffic flows (before and after surveys), but in most of the cases no measurements were taken after the installation of traffic calming schemes. Nevertheless, this report states that assessments undertaken on the Continent have also studied the effect of traffic calming on local businesses (at Borgentreich). The paper concludes with comments on the effectiveness of measures applied to the schemes under study such as that speed reductions have been substantial due to installation of humps, and the proportion of drivers keeping to the 30 mph speed limit increased from 45% to 90%; raised areas were also effective in keeping speeds low. Comments on horizontal deflections, roundabouts, rumble areas and signs, seem to result from observation rather than quantitative measurements.

A review of 20 mph speed zones implemented at 25 sites in the UK (Hodge, 1992) has been restricted to the assessment of safety, and it found that despite insufficient data there are indications of reduction in accident numbers in calmed areas.

An extensive study on the effectiveness of village gateways in Devon and Gloucestershire suggests that gateways can be a useful device for reducing speed by a limited amount (down by between 2.5 and 8 mph) in the vicinity of the measures, in certain circumstances. The speed measurements were made at the 18 sites using a radar gun. The measures included redesigned village nameplates, speed limit signs, road markings, contrasting surfacing, central islands and rumble areas. It was clear that the measures applied often did not reduce speeds enough, therefore more effective measures are required (Wheeler, Taylor and Payne, 1993).

Local area speed limits have also been applied in residential areas in Australia following a widespread trend in traffic management measures. The effects of a 40 km/h local area in the City of Unley have been extensively studied over a period of fifteen months, in contrast to previous studies which confined the monitoring period to a few months after the introduction of the new speed limit. Speed and traffic flow data were extensively collected using automatic classifiers. Due to the length of the monitoring period, it was possible to demonstrate that the initial speed reductions (up to 5 km/h) were maintained throughout the trial. Traffic flows on the roads in the area were unaffected during the trial. The trial was conducted in stages: signs installed, low intensity enforcement and high intensity enforcement in addition to publicity. The increase in the amount of enforcement did not reduce speeds, except on one road where most of the enforcement was concentrated (Cairney and Fackrell, 1993).

2.5.2 Evaluation of Individual Measures

Studies on individual traffic calming measures have been entered in Table 2.2 by type of measure and related impacts. Due to the large amount of information related to each study, this table does not include the name of the authors or speed measurement techniques. This information is provided in Tables 2.3 and 2.4 respectively, together with relevant additional observations.

Before moving further, special comments on three publications which have not been considered in this section, should be made here. 'Traffic Calming Guidelines' (Devon County Council, 1991) and 'Civilised Streets: a guide to traffic calming' (Hass-Klau et al, 1992) provide general technical information on a large variety of traffic calming measures and techniques. Case studies in Britain and on the Continent illustrate different applications of traffic calming in residential streets, city centres and major roads. The assessment of the effectiveness of measures is based on previous experiences and case studies. However, as mentioned before, the assessments seem to result from observation rather than extensive evaluations.

The third publication 'Traffic Calming in Practice' (County Surveyors Society, 1994) provides an assessment of the UK experience in traffic calming through 85 case studies showing a reasonable cross section of schemes in town centres, rural locations and residential areas, and types of measures. Commentaries on the case studies are included together with reference tables summarising their cost, main features and effectiveness, by comparing before and after traffic volume, speed and accidents.

Table 2.2: Evaluations of individual traffic calming measures (key for authors in Table 2.3)

MEASURES / IMPACTS	ROAD HUMPS	RUMBLE DEVICES	CHICANES	SPEED TABLE	CUSHIONS	OTHERS
SPEED	average down 30% [1] average down 55% [2] down by 4 to 11km/h [3] speed/spacing relationship [2,4,11,14] speed/height relation [5] no quantification [6] down 13 to 40% [7] down 21 to 24km/h [8,9] significant reduction [12] speed change relation [23]	painted: minor reduction rumble strips down 40% [15] average 85th down 6% [16] small, significant [17] down 1 to 3mph at 9 sites; up 1 to 5mph at 7 sites [22]	significant reduction [6, 8] down 5mph [9] mean speed: 25 to 30 km/h [20] speed change relationship [23] reductions of up to 20 mph [25]	down 7 mph [9] 14 to 19mph at the device [11]	reduced from 31mph to 15mph (Germany) from 28 to 17mph in England [11] down to 14 and 19 mph according to dimensions [27]	speed change relationships for road narrowing [23] overall reduction of 9mph for 'thumps' [24] 85th down 10mph for low height humps [24]
TRAFFIC FLOW	average down 37% [2] average down 20% [3] down 40 to 50%; up 28% at untreated site [7] down 21% to 24% [8] no changes in one area [9] down 24% [12]	no detectable effect [16] relatively unchanged [22]	slight reduction [6] about the same [9] down 9% [18]	about the same [9]		overall reduction of 23% in the two way flow[24]
TRAVEL TIME	average up 60 to 70% [2,8] average up 37% [3]		up 30.4 to 70.4% [20]			up 6% for buses; 9 to 33% minibuses [24]
NOISE	down 4 to 6 dB(A) [2] from 60.3 to 45.9 dB(A) [3] quieter after [7] very slight reduction [8] overall noise reduced [12]	noise problems less than expected [22] up 5.1 to 6.3dB(A) [16] increased [17] substantial noise [11]			overall traffic noise down 4 dB(A) [26]	
SAFETY	casualties down 61% [2] no indication [3]	accidents reduced [15] insignificant [16] no evidence [22]	no reported injury accident [18]			overall frequency down from 13 to 0.4 per year [24]
DESIGN SUGGESTION	[1,11,12, 13, 14]	[11]	new [18]	[11]	[11]	road surface design [21]
CAR'S VERTICAL ACCELERATION	[5, 10, 13, 14, 19]				[10]	

Table 2.3: Key for authors mentioned in Tables 2.2 and 2.4

[KEY]	AUTHOR	OBSERVATIONS
1	Wit (1984)	design and effects of traffic humps
2	Sumner and Baguley (1979)	design and effects of speed control humps in residential roads
3	Baguley (1981)	further trials of speed control humps
4	Lines (1993)	speed x hump separation relationships
5	Mak (1986)	relationships: crossing speed x undulation height; speed change x undulation height and deceleration rate x undulation height
6	Klik and Faghri (1993)	comparison of humps and deviation stressing the advantages of the latter
7	McNamara (1983)	further work to McNamara [8]
8	McDonald (1983)	off-road tests of road humps
9	Durkin and Pheby (1992)	general evaluation of traffic calming schemes in York
10	Hodge (1993)	effect of humps and cushions on a scale of discomfort
11	Webster (1993)	special design for pedestrians and cyclists
12	Broadbent and Salmon (1991)	mini humps
13	Jarvis and Giummarra (1992)	humps for bus routes
14	Watts (1973)	long and short humps
15	Zaidel et al (1984)	comparison between painted stripes and rumble strips
16	Webster and Layfield (1993)	rumble devices and rumble areas in 35 sites in the UK
17	Watts (1978)	trial specification for dimensions and construction of rumble areas
18	Broadbent and Salmon (1993)	chicane system of islands simulating the effect of cars parked
19	Webster (1993a)	grounding of vehicles on road humps
20	Taylor and Rutherford (1986)	evaluating slow points (chicane) one-way and two-ways
21	Hiddas (1993)	new proposal for a continuous physical vertical alignment
22	Cynecki et al (1993)	testing new materials for rumble strips
23	Engel and Thomsen (1992)	development of speed change relationship due to road narrowing, hump, and lateral dislocation (chicane)
24	Webster (1994)	speed at thermoplastic 'thumps' and low height (50 mm) standard circular profile humps
25	Sayer and Parry (1994)	off-road trials varying the physical dimensions of single and double chicanes
26	Abbott et al (1995)	vehicle and traffic noise measurements alongside speed cushions in York
27	Layfield (1994)	on-road trials of speed cushions in York and Sheffield

Table 2.2 clearly shows that isolated evaluations have been mainly carried out for road humps. The effectiveness and assessment of measures other than humps are usually undertaken in comparison to a hump. Furthermore, only very few evaluations have been carried out for speed cushions and chicanes. Among traffic calming measures presented in Table 2.2, speed humps have been the most successful measure in achieving the greatest speed reductions. Rumble devices have proved to be least effective.

Sometimes the effect of rumble devices on speeds may diminish with time (Webster and Layfield, 1993); however Zaidel et al (1984) found that the effect on driver behaviour did not diminish after a one year period. Quoting Pharoah and Russell (1989), 'speed reduction is used as a key evaluation criterion for traffic calming schemes'.

The off-road trials conducted by Sayer and Parry (1994), determined the relative effects on speed of changing physical dimensions of the chicanes. However, due to the artificial nature of the trial and the small vehicle and driver sample size, the absolute values may not necessarily represent the vehicle speeds that would be achieved on the public road. Therefore, care must be taken as to the interpretation of the results prior to their validation against horizontal deflections installed on public roads.

The effectiveness of speed cushions as traffic calming devices has been assessed by on-road trials in York and Sheffield (Layfield, 1994). The overall width of the cushion was found to be generally a good determinant of mean speeds with wider cushions producing lower speeds. One of the interests in this study relates to the fact that two of its trial sites have been also chosen for this current research.

Impacts on vehicle speeds, as well as on journey time, traffic flows, noise and safety were reported to have been evaluated mainly through "before and after" studies. The use of control areas was reported in a few cases. Many reports do not state the technique or the methodology adopted. Speed measurement techniques have ranged from radar gun, automatic traffic counters, time lapse photography and pairs of road sensors connected to a data logger, the latter in a few cases. Table 2.4 summarises speed measurement techniques involved in the assessment of individual measures earlier mentioned.

Table 2.4: Measurement techniques adopted for some evaluations

MEASUREMENT	TECHNIQUE	AUTHOR	OBSERVATIONS
at the measure	radar gun	[11,13, 14,25]	
	automatic	[11]	
	sensors	[3]	
	no information	[8, 9, 27]	
mid-way between measures	radar gun	[4, 11, 24]	
	automatic	[4,11,22, 24]	
	observer in a car	[14]	
	sensors	[3]	at fastest points
	no information	[2, 8, 9, 27]	
before and after the measure	radar gun	[16]	
	speed/flow tubes	[16]	
	time lapse	[17]	
more than two points next to a measure	radar gun	[23]	3 points (50m before, after and at the measure)
	sensors/data logger	[15]	8 pairs of sensors
	time lapse video	[5]	average speed profile for individual undulations and bump
	radar + detectors + data logger	[20]	speed profile (approach and exit to slow point)
	time lapse film + radar	[3]	average speed profile for 3 humps in sequence
	no information	[1]	at 7 points (approach and exit to a hump)
no information	no information	[6, 7,12,18]	

In contrast to the majority of reports mentioned in Table 2.2, which do not extensively study impacts on speed, Lines (1993), Mak (1986), Webster (1993), Taylor and Rutherford (1986), Hiddas (1993), Engel and Thomsen (1992) and Baguley (1981) have introduced new approaches to the analysis of speed due to traffic control devices. These approaches and their implications for this research will be fully discussed in the next chapter.

Although some studies have assessed speeds midway between humps, Lines (1993) states that "it is likely that the relationships between speed and hump spacing will continue to change over time, and further studies will be needed in the future".

However, the most important measurement approach, to the development of this research, has been the measurement of speed at various points, as adopted in the following cases:

speed profiles for individual undulations and hump, in the USA (Mak, 1986); three humps in sequence resulting in average speed profile for heavy and light vehicles, in the UK (Baguley, 1981); lateral displacement (chicane), humps, and road narrowing by measuring speed at three points (50m before, at the measure and 50m after) and deriving a speed change relationship, in Denmark (Engel and Thomsen, 1992); and speed profiles for slow point one-way and two-way, in Australia (Taylor and Rutherford, 1986). A slow point is a horizontal deflection in the carriageway.

2.6 Implications for the Study

Although a few studies have analysed speed at specific points on the approach to and exit from traffic calming measures, the reviewed approaches have mainly focused on average speed profile rather than individual vehicle profiles. Moreover, the measurements have mainly been restricted to an individual measure. Regarding further speed analysis, studies have generally focused on the development of relationships between speed and hump height and speed and hump separation. Engel and Thomsen's approach predicted speed change relationships due to the installation of certain traffic calming measures. However, the study does not cover installation of measures in sequence.

Concerning the evaluation of schemes, Pharoah and Russell (1989) mentioned that "the effects of individual measures cannot easily be evaluated in isolation from the scheme in which they are embedded. The particular combination of measures in a street has a powerful influence on the behaviour of drivers".

Overall scheme evaluations such as those presented in Table 2.1 have not accomplished the desired degree of depth concerning the knowledge of the effects of individual measures or their effects in combination, since the obtained results are too general. In addition to that, Table 2.2 also demonstrates the lack of a comprehensive evaluation involving interaction between measures. With regard to the study of speed, the more extensive measurements and respective analysis, as presented in Table 2.4, have also confirmed a gap in the study of the impacts of a series of traffic calming measures on speeds.

This assessment has confirmed the appropriateness of the objectives specified in Chapter 1. Hence, this study of traffic calming measures will focus on individual speed profiles as a result of measures in sequence as compared with the usual assessment of average speed on the link.

An additional gap in coverage is the issue of traffic redistribution due to the implementation of traffic calming schemes. The displacement of traffic to surrounding roads may sometimes become a nuisance generating negative and undesired effects. Traffic redistribution has been observed in some scheme evaluations, however it has been treated as a minor issue, since reductions in speed and in the number of accidents are the main concern. In view of a lack of further knowledge on traffic redistribution, this issue was initially also covered in the research objectives. However, during the development of the research methodology, it was excluded since it would require an amount of time and work which would not be possible to fit into the research timetable.

CHAPTER 3

RESEARCH METHODS

The previous chapter has outlined the state of the art in traffic calming and has demonstrated, through the review of studies, the lack of focus on the effects of a series of measures on speeds. Speed has been considered as the most important factor to describe driving style when negotiating traffic calming devices and in this particular case, an important variable to analyse the effectiveness of calming measures. This chapter complements the literature review on specific topics in order to support the research methodology. Consequently, the focus is on methods for surveying speed and travel time.

Applications of technology in speed data collection, mainly designed for the assessment of speed-reducing features, are reviewed. This chapter also presents an overview on models describing vehicles' motion as well as on some of the most important relationships developed towards the understanding of the effects of speed control devices.

3.1 Measurement of Speed

Speed is an important road design parameter, in an overall sense for setting design standards, and in an elemental sense as a measure of the effects of minor changes to traffic streams, such as installing control devices or widening a curve (Taylor and Young, 1988). According to them, there are four principal classifications of speed commonly of interest:

a) spot speed - instantaneous speed of a vehicle at a specified point along a road. The arithmetic average of a number of spot speed observations is the time mean speed and it is an estimate of the true mean at the point under study;

b) journey speed - the effective speed of the vehicle on a trip between two points;

c) space mean speed - journey speed when it is taken to be the speed of all vehicles on a length of road at a given instant of time; and

d) running speed - the average speed over a trip, while the vehicle is moving.

Spot speed data are useful in the study of driver behaviour. They provide estimates of the prevailing distribution of speed at a site under different environmental conditions and of the range of likely vehicle speeds (Taylor and Young, 1988). Spot speeds yield time mean speed, 85th percentile speed, and standard deviations of speeds, and are useful in evaluating:

aspects of physical design of highways: speed, curvature, superelevation, gradient, length of grade;

application of traffic control devices: sight-distance zones, no-passing zones, speed limits, traffic sign location, location and timing of signals;

accident analysis of problem locations;

effectiveness of traffic improvements;

before and after studies;

needed enforcement and effectiveness of enforcement; and

speed trends determined by periodic sampling (McShane and Roess, 1990).

Since the collection of speeds at specific points along a link is the main interest in this research, this review will concentrate on methods of collecting spot speed data.

There are a number of ways to collect spot speed data depending upon the equipment available and the approach to be used. Indirect methods involve the estimation of speed from a travel time observation such as measuring the travel time of a vehicle between two detectors separated by a fixed distance. Direct methods enable measuring speed directly on the basis of the Doppler principle.

3.1.1 Radar Meters

This is a direct method for recording speeds. The operation of radar speed meters is quite simple. It gives the individual speeds of vehicles directly as traffic approaches or goes away from the observer. The meter is positioned at the edge of the roadway at an angle of approximately 10°. The device is easy to set up and operate and should be inconspicuous to reduce influence on drivers' behaviour. Radar speed meters are suitable for relatively narrow roads at low or medium flows, when vehicles travel past the observer individually. They are not able to measure speeds of cars as they actually pass the observer and it is difficult to distinguish vehicles under high volume conditions. Data may be biased if two vehicles are passing each other or if the observer is visible. Measurements can be made from inside a parked car, but the car should not be parked in any location which affects the speed of the vehicles surveyed (TRL, 1993).

3.1.2 Enoscope

The device consists of a simple open housing containing a mirror mounted on a tripod at the side of the road in such a way that the observer's line of sight is turned through 90°. The technique of measurement consists of two enoscopes set on tripods, a measured distance apart. The observer times the passage of a vehicle through the section using a stop-watch (Hobbs, 1979). It is a simple and inexpensive item, but considerable time is required to time each vehicle and human error can easily occur. Under high volume conditions, it may be difficult to relate the observation in the mirror to the correct vehicle, resulting in the observer “losing” the sampled vehicle (Kennedy et al, 1973).

3.1.3 Electronic Timing

One of the applications of data loggers is for recording speeds. The passing time of a vehicle between two detectors (e.g. road tubes, treadle sensors, optical sensors) a measured distance apart, is recorded. The impulses generated by those vehicle detectors are transformed into readable signals by a device connected to the detectors, enabling the signals to be recorded by a data logger. This method results in a high level of accuracy, and allows data to be collected from a number of detectors simultaneously. Nevertheless, the use of visible vehicle detectors may affect driver behaviour and distort the speed distribution.

Vehicle Detectors

Detectors to indicate the presence of vehicles are twofold (Taylor and Young, 1988):

a) point (axle) detectors: operating by recognising certain parts of a vehicle, usually the wheels and registering the passage of these points. Among the types of axle detectors are:

- pneumatic tubes which were the first traffic measurement device and are still used for temporary measurements. The passage of a vehicle wheel compresses the air in the tube and the resulting change in pressure is detected;

- treadle detectors using electrical contact switches (the tyre pressure forces two copper contacts together);

- 'Jarvis brick' optical detectors which consist of an infra-red beam transmitter-receiver and a retroreflector. The detector unit is positioned on one side of the road, and the retroreflector on the opposite side. A pulse is registered each time a vehicle cuts the beam (Taylor and Rutherford, 1986). This detector could be used to indicate vehicle presence (the beam remaining broken as long as the vehicle is between the transmitter and the retroreflector), but the main application has been for axle detection, with the units mounted close to the road surface so that the beam passes under the body of the vehicle, but it is cut by the wheels (Taylor and Young, 1988);

- triboelectric cables consist of a coaxial cable with a central conductor made of wires and surrounded by a dielectric material, with an outer ring of loosely intertwined wires, and encased in a tough plastic jacket. This cable is pressure sensitive and when an axle passes over it, the wires rub the surface of the dielectric causing additional electric charge to accumulate. This accumulation of charge can be registered, detecting the axle. The triboelectric detector can be compared to the pneumatic tube with the advantage of being less visible as it has a very small diameter (Taylor and Young, 1988);

- piezoelectric cables consist of a solid copper conductor surrounded by a compressed ceramic powder and enclosed in a copper sheath. Its composition suggests that the cable could be used for direct in-motion recording of axle weight as well as axle passage (Taylor and Young, 1988); and

b) vehicle presence detectors: indicate the passage or presence of a vehicle. Among the types are:

- inductive loop is the most widespread measurement technique. It is made of several turns of wire which are buried in the carriageway. The self inductance of the coil is modified by the passage of the metallic mass of a vehicle. Inductive loops are commonly used for traffic counting purposes, but when loops are used in combination, they allow information on other traffic data such as speeds and vehicle classification;

- ultrasonic sensors operate by emitting a wave train and listening to the echo. A vehicle is detected in the sensor's detection zone by a reduction in the time taken for each echo to return. This method is most used on urban motorways to provide information to road users as it has a poor performance in terms of accuracy of speed measurements. (Espié and Lenoir, 1991);
- video-based methods for vehicle detection can provide data on vehicle trajectories, headways and flows, and speeds;
- radio transponders fitted in the vehicle are capable of emitting continuously coded signals which are received at fixed stations in a transport network allowing the presence of the vehicle to be recorded as well as the time spent in a subarea in the network to be deduced, therefore, producing information on travel time and origin-destination trip data. This system may also be applied to road pricing control and route guidance (Taylor and Young, 1988); and
- microwave utilising the Doppler effect, is becoming popular for speed monitoring (e.g. via transceivers fixed on overheads gantries or bridges (Bonsall, 1992).

Another way of vehicle detection is through the direct observation by a person. The human observer is the most versatile of all detectors, being able to receive and interpret signals from visual, audible, tactile and olfactory sources. Humans are able to perform complex recognition tasks, namely vehicle type, vehicle occupancy, vehicle manoeuvres and driver behaviour. However, automatic detection systems are preferred in situations where observers cannot cope, such as continuous surveys over considerable periods of time, and also when high rates of instantaneous recording are necessary.

Data Loggers

The next stage after vehicle detection in the data collection process is related to the recording and initial processing of data. Various technologies are now available for logging traffic data in the field, using microprocessor and microcomputer systems, to record and process information. Microprocessor technology has enabled the development of portable traffic analysers that cope with multichannel inputs and auxiliary inputs applied by the observer. Powerful traffic counter/classifiers commercially available are designed to cope with a range of tasks in traffic data collection. This issue has been further discussed in Chapter 4, section 4.3.1.

3.1.4 Video-Recording Methods

Time-lapse photography using 16 mm film cameras was a relatively popular method of recording speed and other traffic data, in which the image of traffic streams are taken at precise intervals, but became too expensive for general use. Time-lapse photography lacks the advantage of checking the recorded data in the field and has a 'jerky' image or playback (typically two to four frames per second). In addition, extensive use of time-lapse projectors induces significant equipment wear-and-tear (McShane and Roess, 1990). Therefore, this technology has been supplanted by video recording.

The recent advances in video-cassette recording systems mean that video is a useful alternative. This method is useful in congested traffic and can be used to record distance covered in unit time (e.g. time between the frames) or time to cover given distances (e.g. via distance marks annotated onto the screen or marked on the roadway) (Bonsall, 1992).

The advantages of the method are: a permanent and complete record of traffic flow, which can always be re-analysed and re-examined and a considerable amount of information, for instance, vehicle classification, occupancy, speed, flows, headways and overtaking. The disadvantages are the time-consuming nature of the subsequent analysis and the error resulting from parallax. However, the recent developments on computer-based image processing technologies should reduce the time consumed for data analysis (Taylor and Young, 1988).

3.1.5 Applications of Technology in Speed Data Collection

The road trials of speed control humps undertaken by Baguley (1981) included a separate study (at one road) of vehicle speeds carried out to determine the longitudinal pattern of speeds adopted by drivers (speed profiles) over the stretches of road in between humps.

The speed measurement technique consisted of a radar speed meter linked to a time lapse camera in a tripod-mounted frame. The radar was aligned so that a vehicle viewed in the centre of the camera viewfinder could be tracked along the road by the radar gun. This system was placed on the 7th storey of a tower block to provide a good observation point for the 200 metres link. In order to achieve correct measurements, correction factors were used to adjust the interval between the radar gun readings and the relative vehicle position. For this purpose white tape distance markers were applied on the pavement.

Speed profiles at four 'slow points' (one and two-way) were obtained by Taylor and Rutherford (1986). A 'diagonal slow point' is a speed control device which implies a horizontal deflection in the carriageway and its main design parameters are the device length, the angle of deviation and the road width at the device. The data collection system comprised a data logger to record times at which a vehicle crossed a sequence of detectors and a radar speed gun to measure the speeds at which the vehicle passed each detector. The vehicle detectors were the 'Jarvis brick' photoelectric beam developed at the Australian Road Research Board.

The measurement technique consisted of registering a pulse when a vehicle cut the beam, and the arrival time was recorded by the Vehicle Detector Data Acquisition System (VDDAS). When this happened an observer, triggered by the sound signal from the VDDAS, recorded the vehicle's speed using the radar gun. Speeds could have been measured using 'amphometer pairs' of detectors, but there were not enough detectors available at the time of the experiment. 'Amphometers' are often used by the police in some States of Australia, to measure vehicle speed for enforcement purposes, using visible sensors.

Pitcher (1989a) obtained speed profiles of isolated vehicles travelling in residential streets. The adopted data collection system consisted of 16 steel electro mechanical treadle sensors connected to a VDDAS data logger, designed by ARRB, via lengths of electrical cables. VDDAS units are based on a single board microprocessor controller and data retrieval is carried out via a compatible laptop computer loaded with specific software. Pitcher also recorded other characteristics of the vehicles and of the site manually as the data logger recorded only the detector number and the elapsed time. Therefore, the time of entry, the direction of travel, the number of parked vehicles in the street, the type of vehicle, the type of trip and conflicts affecting vehicles' speed were manually recorded. Detector pairs at a known distance apart were used to establish the wheelbase of the vehicle.

Seco (1991) used a series of road tubes connected to air-switches to measure spot speeds and passing times in order to study drivers' behaviour at uncontrolled junctions. Information provided by the road sensors were retrieved by a data logger produced by Golden River. The communication between the data logger and a personal computer was done via software developed for that specific situation. The personal computer was used in order to store the information as the data logger memory could not cope with the size of the files. A pair of pneumatic tubes at a known distance apart were again used to establish the wheelbase of the vehicle.

Three Vehicle Data Acquisition System (VDAS) traffic classifiers units, also designed by ARRB, were used for traffic speed measurements conducted by Donald (1994) in order to study the effectiveness of a variety of sign types in reducing speeds. Two treadle detectors placed 5 metres apart, and attached to each VDAS unit, were used to detect passing vehicles. Each of the three VDAS units collected detailed data about every vehicle crossing the detectors, such as time, date, classification number, number of axles, speed of the vehicle, headway and the wheelbase. The identification of a particular vehicle across the VDAS units was enabled through a computer program developed to follow each vehicle by matching information from the three files.

Tan and Ward (1993) also used three VDAS units to collect speed data. In this specific study of the effectiveness of 90° bends in controlling speed on urban local roads, VDAS were preferred to other techniques because the speed could be obtained unobtrusively (no need for an observer), for at least a 24 hour period. Speeds at the 90° bend, mid-point between the bend and end slow point (e.g. stop, give-way, T-junction), and 20 metres from the end slow point were collected at 11 test sites.

Driving Simulators have been used to assess speed reducing measures. They allow total control of the roadway and the traffic environment in addition to the investigation of novel treatments which would not be appropriate for on-road trials until their effects are fully assessed. Nevertheless, the main restriction of this technique is related to the assessment of measures which result in vehicles' vertical movement as the driving simulator cannot cope with these vertical movements. Therefore, the feasibility of this technique has been assessed through the simulation of horizontal deflections to the carriageway as mentioned in the following two studies.

An assessment of the validity of a driving simulator in evaluating speed-reducing measures was carried out by Riemersma et al (1990) using the Daimler-Benz simulator in Berlin. It is an advanced driving simulator which uses computer generated images within a cylindrical-shaped projection dome with a complete car positioned inside the dome. That project was based on the comparison of results obtained in the driving simulator with the actual changes in driving behaviour after the implementation of speed-reducing measures in reality. Three measures (portal gate, coloured asphalt and median strip) and seven possible combinations of these measures were tested along 500 metres before the village entrance and 200 metres after it. Speed profiles were derived as a function of instruction to subjects and of absence (before) or presence (after) of the three measures. According to the authors, the tests demonstrated the feasibility of the technique to analyse the effectiveness of speed-reducing measures. The measures under consideration did not involve vertical shifts to the carriageway.

Speed on rural arterial roads have been investigated using the Advanced Driving Simulator at the University of Leeds (Pyne et al, 1995). This facility is a sophisticated, static-based simulator built around a Silicon Graphics Reality Engine workstation. It consists of a complete car with all basic controls, situated in front of a projection screen. The interaction between the driver activation of the vehicle controls and the resulting driver view projected onto the screen is continuous. The effectiveness of a variety of speed reducing measures appropriate to rural single-carriageway arterial roads has been investigated through simulated roads. Measures under consideration comprise the use of road markings to reduce lane width or produce horizontal deflection; the use of signs; and the use of optical illusions to affect the driver's perception of speed or road width. Further tests will be carried out to evaluate combinations of treatments. Vertical deflections might have been applied to rural arterial roads, but they could not be evaluated by the Driving Simulator due to its limitations.

3.2 Measurement of Travel Time

Travel times may be observed in two different ways. The first way involves stationary observer methods, where observers placed at fixed points in the network record the times that a sample of vehicles take to travel the length of the survey section. The second way involves moving observer methods where the observer drives a test car in the traffic stream and records its passage time (Taylor and Young, 1988).

According to Bonsall (1992), Kennedy et al (1973), Taylor and Young (1988), Department of Transport (1991), Box and Oppenlander (1976) and May et al (1989), among the alternative procedures and strategies for data collection on travel time are:

3.2.1 Registration Plate Methods

Registration plate method is used if some information concerning the entrance and exit points of the study area is desired. Travel time can be deduced by matching records of times at which the plate was seen at the two locations. Partial records (three numbers plus one letter of the plate) may be sufficient. There are various ways of recording (Bonsall, 1992):

a) pencil and paper (manual recording) - using a 10 minute recording sheet divided into boxes, each of which is used for 15 seconds if the stations are far apart or with precise times noted. The method is cheap and quick to organise but is error prone and transcription is time-consuming;

b) audio tape - observers are able to cope with fast vehicle streams. It produces higher data rates, but transcription is time-consuming;

c) data loggers - avoid transcription problem and the automatic time base is very accurate. The method needs good equipment and software;

d) video recording of plates - the method also needs good equipment with high definition. Manual transcription is time-consuming, and automatic transcription can achieve 75% accuracy;

e) photographic methods - Time-lapse photography has also been used successfully in some studies (DoT, 1991). This technique is applicable to a short test section only. However, the recent advances in video camera technology and also in video-based vehicle detection, for example the ability to read number plates by direct coupling a video camera to a computer, has definitely supplanted time-lapse photography.

The use of automatic methods avoid errors associated with manual recording. However, the use of a Psion Organiser (data logger) has proved to be difficult to cope with fast vehicle streams, mainly due to the unusual (and small) keyboard layout. In high volume conditions associated with fast streams, even the use of audio tape may record some biased readings since the observer changes the point of reading to be able to catch the greatest possible number of vehicles. Therefore, this indicates the need of well-trained observers to minimise likely data distortions.

3.2.2 Vantage Point Methods

From vantage points such as high buildings, telescopic masts, and tethered balloons, an observer can determine the travel time and detailed path of a vehicle, either by direct observation (observer with a stop-watch) or from video recordings. Vehicles are timed at predetermined points. The use of video allows recording of vehicle type, headways, lane usage etc. Care must be taking with sampling to avoid the temptation of timing the next vehicle instead of using predefined intervals (Bonsall, 1992).

3.2.3 Input-Output Method

The input-output method provides estimates of mean travel times but does not try to match individual vehicle observations at different stations. This method finds the mean arrival time and departure time of the traffic stream in the test section, and calculates the mean travel time by subtracting mean departure time from mean arrival time. The data collected at each station are the number of arrivals in successive time intervals and the data obtained are mean travel time and flow. This method can be applied to road sections, junctions and traffic control devices. Since this method requires the same group of vehicles to be recorded at each station, it is best suited to closed systems, in which vehicles entering the survey zone will leave it via the observation points e.g. freeway traffic, recording the duration of stay of vehicles in an off-street car park (Taylor and Young, 1988).

3.2.4 Moving Vehicle Methods

Information on flows, speed, running and journey times can be obtained conveniently by observers in moving vehicles (DoT, 1991). It utilises a test vehicle, a driver and an observer, and a data recording system to make a series of test runs. The survey vehicle is driven along a pre-determined route, at the typical speed of other vehicles. Observers in the vehicle record the time at pre-determined timing points and the duration and cause of all stops and delays (TRL, 1993). The data recording may be by paper, pencil and stopwatch, laptop microcomputer or by an instrumented vehicle (Taylor and Young, 1988). There are various methods with various levels of sophistication:

- simple journey timing method: observer in vehicle notes time and landmarks;
- corrected moving observer method involves recording the number of vehicles overtaken and overtaking, number of vehicles met in opposite direction and time taken in both directions to obtain mean and variance of travel times, stopped time and running time and number of stops in long road sections; and
- floating vehicle to obtain mean travel time, stopped time and running time, flows and number of stops also in long road sections. The test vehicle is driven so that the number of vehicles overtaken is the same as the number of overtaking vehicles. The test vehicle is then travelling at the mean speed of traffic (DoT, 1991).

3.2.5 Other Methods

Other methods of measuring travel time may apply (i) panels of drivers recording journey times for a period of days or weeks, and (ii) automatic methods such as induction loop fingerprint for very short stretches of road, and two-way route guidance systems which automatically record link travel times of equipped vehicle. Automatic recording methods may also use GIS - geographical information system or a road user guidance device for instance utilising infrared beacons, which monitor traffic flows, located throughout the network in communication to the vehicle and the control room (e.g. Ali-Scout, Autoguide, Uliisse) (Espié and Lenoir, 1991).

3.3 Detailed Analysis of the Effects of Speed-Reducing Measures

Although the term speed-reducing measure allows a broad interpretation and may range from simple road signing to extensive road geometry lay-out changes, in this context, the term has been specifically applied to usual traffic calming measures. Some of the studies described here have already been briefly commented on with regard to the data collection technique, in the previous chapter.

The relationship between speed and hump separation has been the subject of many studies in the UK. Initial TRL research comprised a comprehensive trial of different hump lengths and heights (Watts, 1973). Subsequently, Sumner and Baguley (1979) and Baguley (1981) conducted further trials in relation to vehicle speed midway between humps and hump separation.

Baguley's speed profile study determined the position where maximum speed between humps is attained. He expressed it as a proportion of the hump separation and the results were quite consistent over the three spacings studied. The point of maximum speed was found to be 0.61 of the hump separation measured in the direction of travel with a 99% confidence limit of ±0.07. This study also suggested no statistically significant difference for the position of maximum speed calculated for the two vehicle categories under consideration (light and heavy vehicles).

Mak, (1986) used time-lapse video photography to conduct a speed study for two series of undulations, one with five and the other with two undulations. Linear regression equations relating undulation height to the crossing speed, the speed change, and the deceleration were developed as follows:

$$\textit{Crossing speed} = 35.03 - 5.13 \times (\text{undulation height}) \qquad R^2 = 0.67$$

$$\textit{Speed change} = 16.89 - 5.92 \times (\text{undulation height}) \qquad R^2 = 0.92$$

$$\textit{Deceleration rate} = 12.00 - 4.34 \times (\text{undulation height}) \qquad R^2 = 0.51$$

where: *crossing speed* = speed at the device (mph);

speed change = difference between approach speed (50 ft before the device) and the speed at the device (mph);

deceleration rate = deceleration rates (ft/sec^2) at 50 ft before the device and at 50 ft from the device, respectively;

undulation height = height of the device in inches.

Mak concluded that although the crossing speed was affected by the height of the undulation, the approach speed was not. In other words, the vehicle speed between undulations is not a function of the undulation height. Spacing between undulations may be a more important factor for traffic speed between undulations. However, it was not possible to evaluate the effect of spacing between undulations because a uniform spacing of 300 ft was used.

An instrumented-vehicle study was also conducted by Mak to examine the vertical acceleration, measured in g-forces, experienced by the vehicle and its occupants while crossing the undulation and speed bump. The undulation design differed from the speed bump in that it has a length (in the direction of travel) of about 12 ft, whereas a speed bump length varies within 3-36 inches. Linear relationships were also found relating vehicles' vertical acceleration to vehicle speed. The vertical acceleration experienced by the vehicle increases with higher crossing speed for both undulations and conventional speed bumps.

Taylor and Rutherford (1986), assessing 'diagonal slow points', found that the crossing speeds at the slow points were determined more by the physical properties of the device than by the approach speeds, given variations in the behaviour of individual drivers, i.e. there were no apparent 'end effects'. The observed mean crossing speeds vary from 25 to 30 km/h and the effects of the devices are localised to the vicinity of the device, within a zone of influence of about 80 m. In the analysis of speed distribution, significant skewness was observed for speeds in the vicinity of the slow point, whereas approach speeds outside the zone of influence were not skewed. This led to the hypothesis of using the coefficient of skewness as an indication of the extent of the zone of influence.

Hiddas (1993) observed that the installation of discrete physical control devices (e.g. humps, raised thresholds or chicanes and angled slow points) at regular or irregular intervals creates significant variations in the speed of a vehicle travelling along a treated road which is determined by the following parameters of the device:

(a) its type and geometry which determine the speed at which vehicles will negotiate the device; and

(b) spacing between devices which determines the maximum speed between two successive devices, as drivers tend to accelerate when leaving one device, then decelerate again when approaching the next device.

In order to overcome this speed variation Hiddas suggested a continuous physical control device introducing a vertical alignment (road profile) based on a continuous sine wave. Such a profile provokes continuous change in vertical acceleration, which may deter drivers from exceeding a given critical speed.

Lines (1993) has updated the relationships earlier developed at TRL. Further speed measurements were carried out, often using radar speed guns, and in this case only speeds of 'lead' vehicles travelling under free-flow were recorded. However, at some sites automatic measurements have recorded speeds of every vehicle including those whose speed was affected by the vehicle in front. Based on these data, relationships were developed for circular-profile and flat-topped humps (1:8 gradient) as follows:

circular-profile: $V_{ave} = 12.10 + 0.092S \quad r = 0.87$

$$V_{85} = 16.73 + 0.087S \quad r = 0.80$$

flat-topped: $V_{ave} = 10.50 + 0.087S \quad r = 0.86$

$$V_{85} = 13.97 + 0.080S \quad r = 0.91$$

where: V_{ave} is the average speed midway between measures in mile/h

V_{85} is the 85th percentile speed midway between measures in mile/h

S is the separation in metres

r is the correlation coefficient

Lines concluded that the latest speed measurements have indicated that relationships between vehicle speed and spacing has changed for 100-mm high circular-profile humps, compared to measurements taken in the 1970s.

The report presented by Webster (1993) focuses on the assessment and effectiveness of some of the types of vertical deflections, and it also presents speed versus separation relationships for circular profile and flat-topped road humps. The speeds were measured approximately midway between humps. Webster presented identical relationships for circular profile. The relationships for flat-topped humps are as follows:

$$V_{ave} = 11.06 + 0.090S \quad r = 0.91$$

$$V_{85} = 12.95 + 0.107S \quad r = 0.93$$

These relationships differ from those earlier presented by Lines. The difference is easily noticed through a comparison of the flat-topped hump separation requirement to achieve a target speed (20 mph in this example) midway between humps as shown in Table 3.1.

Table 3.1: Comparison of speed vs hump separation (flat-topped humps)

target speed midway between humps (mph)		approximately hump separation required (metres)	
		LINES	WEBSTER
V_{85}	20	75	60
$V_{average}$	20	110	100

The likely reason for this difference may be related to the fact that Webster refers to a 100 mm high hump, with an average slope of 1:10 (in contrast to 1:8 gradient reported by Lines). Furthermore, Webster highlights that those formulae give mid range values of expected speeds and will vary from site to site.

Changes in speed have been analysed by Engel and Thomsen (1992) through an extensive speed data collection obtained from 1,002 road sections. Measurements were taken at the centre of the measure and at 50 metres away from it both upstream and downstream. According to the design standards of 30 km/h streets, measures have to be implemented within a maximum distance of 100 m. Using regression analysis, such data has enabled the development of a model for the calculation of expected speed changes at individual road sections as a consequence of the implementation of a specific type of measure. This model explains 61% of the speed change through the following variables (the respective coefficients are not presented here):

constant factor

before mean speed (upstream speed)

distance to the measure

square distance to the measure

Ln (1 + 1/distance from the measure to the previous measure*)

Ln (1 + 1/distance from the measure to the next measure*)

height of the hump (if a hump is present)

if a single lateral dislocation is present

if a double lateral dislocation is present

if a street narrowing is present.

In the examples of the model application presented in the paper, previous and next measures(*) can be another speed reducing measure or a junction or a speed limit sign. The model does not taken into account the type of previous/next measures, thus it only considers the effect of the measure to be implemented. Moreover, the only variable related to the previous and next measures considered in the model, is the distance to the measure to be implemented. The model predicts the reduction in the mean speed at a given distance to the measure to be implemented.

As the authors put it, the main findings as a result of the model are:

(i) the height of the hump has proved to be of greatest importance to speed change. Per 1 cm in height, there is an expected speed reduction of one km/h; and

(ii) the presence of a street narrowing will reduce speeds by 4.7 km/h and so will the presence of a double lateral dislocation. A single lateral dislocation will account for only a 2 km/h speed reduction.

In summary, the studies have mostly concentrated on relationships between speed and the device height, type and separation of devices.

3.4 Models Describing Vehicle Motion

The interactions between a vehicle and some traffic calming measures can be described by establishing the relationship between the speed of a vehicle and the distance travelled by that vehicle along a pre-determined calmed link.

According to Gerlough and Huber (1975) drivers' goals may be broken down into categories of action, namely perception, judgement, decision and control. The driver's control actions are limited to control of acceleration (braking and accelerating) and control of heading (steering or tracking). Acceleration and deceleration vary widely between vehicle types, from driver to driver, and due to differing weather and traffic conditions (Pitcher, 1989a).

The acceleration control tasks related to vehicle performance characteristics have been the subject of much research especially in Australia, as verified by Pitcher (1989a). It has been particularly associated with the issues of fuel consumption and emission control. A brief review of models of acceleration and deceleration has been conducted in order to establish a theoretical basis to support the research methodology especially in relation to modelling speed profiles of vehicles.

Samuels (1976) established the feasibility of the radar speed meter techniques to obtain vehicle acceleration/deceleration data. This work was done in order to review design standards presented in the 1965 American Association of State Highway and Transportation Officials - AASHTO which are the results of measurements made in 1938. Further work was carried out to investigate the performance capability of modern vehicles under controlled test conditions. This research enforced the need to assess vehicles' acceleration and deceleration satisfactorily.

Jarvis (1987) studied the in-service acceleration behaviour in relation to its effect on the distances needed to change speed between a range of initial and final design values. The purpose of the study was to provide a rationale for the design of acceleration lanes. The speed profiles of vehicles were monitored as they left a rural intersection from low speed to a cruise speed. Data was collected using a series of either metal strip or pneumatic switch detectors fixed to the carriageway. This research indicated that the acceleration component of the velocity-distance relationship could be explained by an equation of the form:

$$v^3 = a + bx + cx^2$$

where v = vehicle speed

x = distance from beginning speed change

and a, b, c = coefficients

and the distance in metres to reach cruise speed (Dc) is: $Dc = -\ b/2c$. Cruise speed models were developed considering six nominal cruise speeds (from 50 to 100 km/h) in 10 km/h steps. Therefore six speed/distance relationships of the form above were achieved.

In addition to the work on vehicle performance characteristics, studies on the issues of fuel consumption and pollutant emissions were conducted in order to develop a model of the acceleration and speed profiles of vehicles. Akcelik, Biggs and Lay (1983) described three new models of acceleration profile (a two-term sinusoidal, a three term sinusoidal, and a polynomial model) in addition to the previously known constant and linear-decreasing acceleration models. The sinusoidal and polynomial models yield the S-shaped speed profile indicated by data from driving in real-life traffic conditions. The results of comparative evaluation reported the polynomial model as the best overall for predicting acceleration distance and fuel consumption, and the linear-decreasing acceleration model as inferior to the other models tested. These models were based on speed-time data collected by means of an instrumented car in urban, suburban and rural road conditions using the chase-car method.

Further work on modelling car fuel consumption was undertaken by Biggs and Akcelik (1985) to extend and refine earlier estimation techniques. The polynomial model of acceleration profiles could be simplified and used to model deceleration profiles. The research line adopted by Akcelik, Biggs and Lay, has derived models under time based relationships of acceleration and velocity, that is acceleration-time and velocity-time relationships.

Usually there is a large variation in acceleration data collected as reported by Akcelik and Biggs (1987). However, acceleration profiles and speed profiles, which refer to acceleration-time and speed-time trace of a vehicle during an acceleration from an initial speed of v_i to a final speed of v_f, can be fairly represented by typical profiles in Figure 3.1.

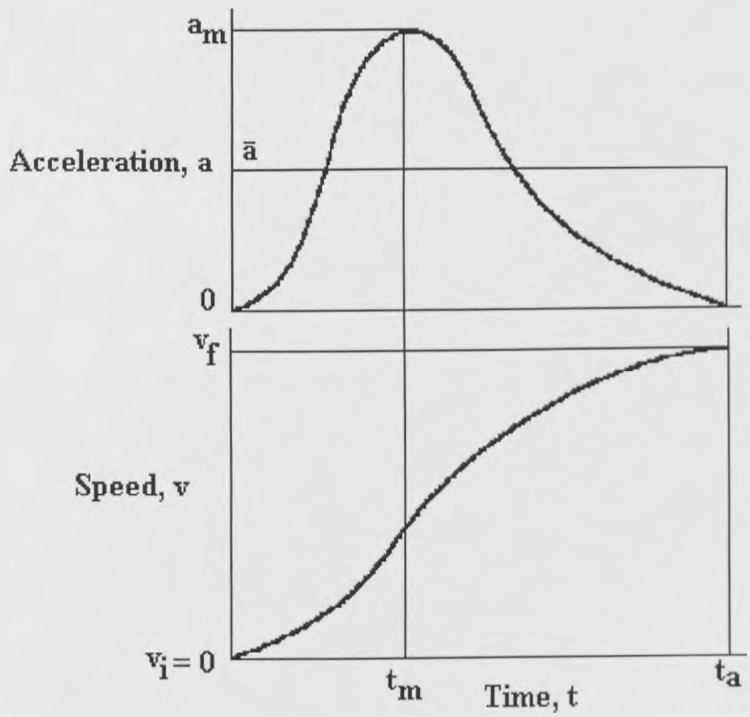


Figure 3.1: Typical acceleration profile (Source: Akcelik and Biggs, 1987)

The notation for Figures 3.1 and 3.2 is as follows:

a_m = maximum acceleration or deceleration;

t_m = time of maximum acceleration or deceleration;

t_a = acceleration time (i.e. total time to reach the final speed);

t_d = deceleration time;

$\bar{a}$ = average acceleration.

Acceleration-time and speed-time traces during a deceleration have the typical shape shown in Figure 3.2 which are almost mirror images of the profiles for acceleration but with the time of absolute maximum acceleration occurring later (Akcelik and Biggs, 1987).

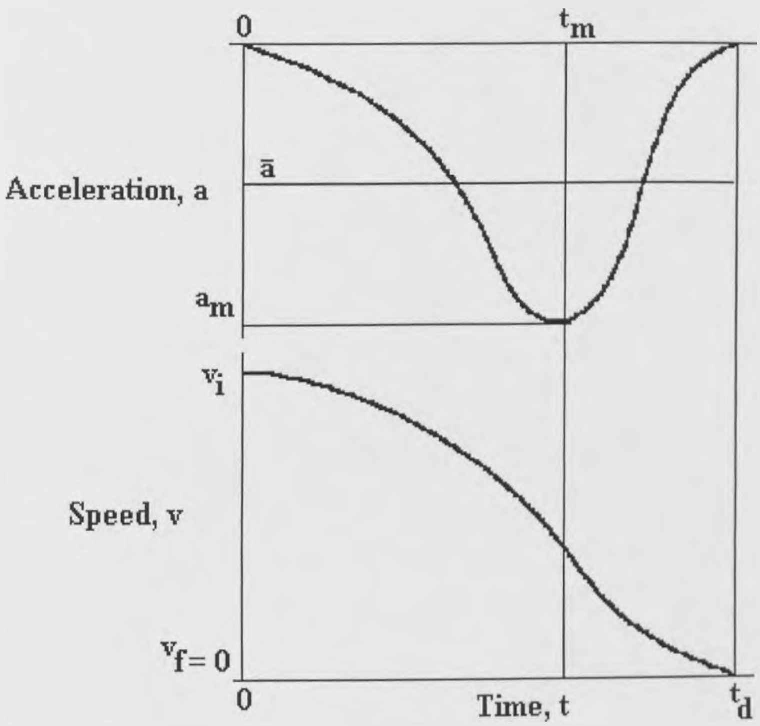


Figure 3.2: Typical deceleration profile (Source: Akcelik and Biggs, 1987)

Lay (1987) examined the work done by Biggs and Akcelik to determine the validity of their results. He derived a segmented power (exponential) model to explore acceleration-time relationships. The parameters in this model were seen to be independent of each other and to contain a great deal of driver variability.

Speeds in residential areas have been the object of many investigations. Bennett (1983) analysed the results of extensive speed measurements mainly in traditional straight residential streets. He derived a predictive model for speed-distance relationships on straight sections of streets, emphasising that the models are purely predictive and the straight lines representing the speed-distance relationships are convenient to use and appear to fit the results as accurately as the curves one might expect.

Another approach to study vehicle speeds on residential streets was conducted by Taylor (1983) aiming to provide information about the relationship between vehicle speeds and flow rates on residential streets. Data collected by means of a radar speed meter and manual classified counts were used to obtain empirical relationships between mean speed, traffic volume, opposing volume and road width applying multiple linear regression.

Still referring to speeds on local streets, Taylor (1984 and 1986) described models based on particular mathematical theories, amenable to use with speed profile data, to explain the effect of speed control devices. Firstly, vehicle performance was described through a typical speed-distance profile on an ordinary street, which includes acceleration, cruise, and deceleration. The simple form $v^2_{(x)} = v_0^2 + 2ax$ assuming constant acceleration and deceleration over time, was applied to the three stages of the speed-distance profile. Subsequently, Taylor studied the effect of a speed control device which imposes a zone of influence on the speed profile of a vehicle, as shown in Figure 3.3, consisting of the device plus deceleration and acceleration lengths surrounding it.

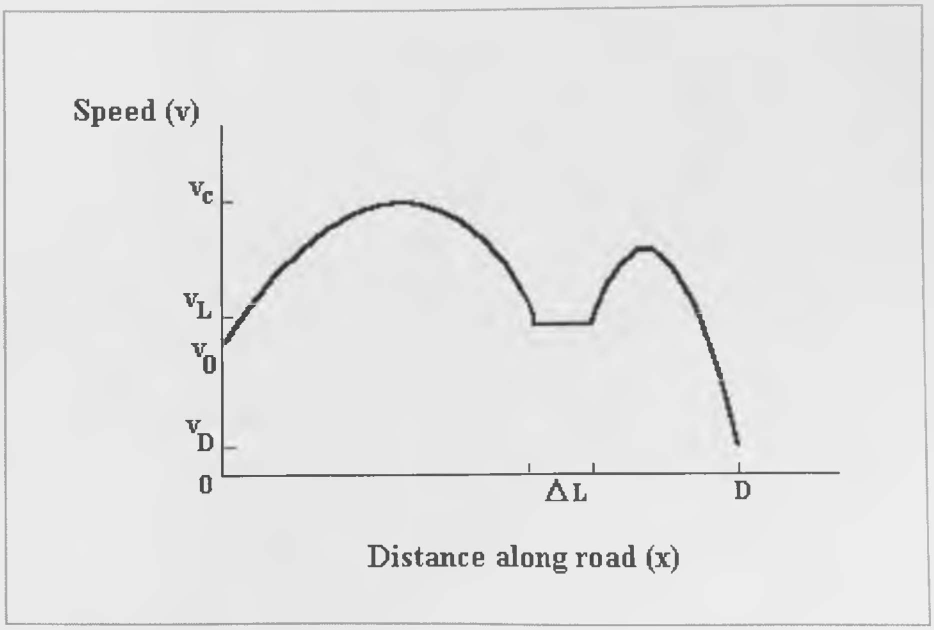


Figure 3.3: Speed-distance profile on a street with a control device (Source: Taylor, 1986)

The extra travel time due to the effect of a speed control device was expressed by a relationship of the form:

$$\Delta t_L = \frac{v_c(a+d)}{2ad}\left(1-(v_L / v_c)^2\right)+\frac{\Delta L}{v_L}(1-v_L / v_c)$$

where: Δt_L = the extra travel time

ΔL = physical length of the device

v_c = the cruise speed

v_L = the speed at the device

a = the acceleration rate

d = the deceleration rate.

According to Taylor (1986) that vehicle performance model may be used to examine planning objectives for the regulation of vehicle speed on local streets, using the mathematical theory of control, and the theory of differential games (based on a two-player game), to establish models which can predict the optimum spacing and location of control measures to meet objectives such as an overall maximum mean travel speed. The models and data were expected to test the hypothesis that measures such as road humps or slow points are not particularly effective means for controlling speeds along roads, but are point measures influencing speeds only in their vicinity. However, it seems that these models were not tested.

Speed profiles of isolated vehicles in residential streets were investigated by Pitcher (1989a) to establish the influence of the length of a section of road on the speed of vehicles. In the development of a speed profile model two approaches were considered: (a) the use of a theoretical basis and (b) the collection of data to enable the development of a numerical model. The latter was adopted since theoretical models related both the acceleration and deceleration components of a vehicle's behaviour to time. Moreover, these models probably overestimate accelerations within the 0-20 km/h range and do not satisfy the requirement addressed by Akcelik et al (1983) which suggests an S-shaped speed profile during acceleration. In addition, some models were also developed based on the acceleration of an average vehicle which restricts their application.

The quadratic function used by Jarvis (1987) was considered by Pitcher not applicable to a residential environment because it was related to the design of acceleration lanes which by nature are installed in high speed environments. Furthermore, Jarvis was not concerned with the acceleration performance of vehicles in the initial stages of their speed profile. Jarvis's study demonstrated that a quadratic function can be used to describe the relationship between speed and distance for higher speeds. However, the initial stages of the profile (S-shaped curve) contravene the quadratic relationship, and hence the relationship fails to describe the whole profile. An equation of that form indicates high initial acceleration rates at the start of the manoeuvre which in reality do not exist. Therefore, it could only be used under conditions where a vehicle has commenced its acceleration and passed the initial problem area. The same situation applies for the case of a vehicle's final deceleration manoeuvre.

However, Pitcher considered that the proportion of the distance travelled which involved overcoming the problems of initial acceleration and final deceleration would be insignificant when compared to the overall length of the street. Therefore, the speed profile of isolated vehicles travelling on residential roads, for the average vehicle and the 85th percentile representative vehicle, was expressed through equations of the same form as Jarvis's, as follows:

a) for an average vehicle:

acceleration $v^3 = -32 + 45x - 0.19x^2$ $\quad 0 < x < 120$ m

deceleration $v^3 = -1780 + 80x - 0.36x^2$ $\quad 120 < x < 200$ m

b) for the 85th percentile:

acceleration $v^3 = -81 + 65x - 0.27x^2$ $\quad 0 < x < 120$ m

deceleration $v^3 = -1830 + 106x - 0.49x^2$ $\quad 120 < x < 200$ m

where: v = speed (in m/s) and

x = distance (in m)

3.5 Conclusions

The review of literature presenting detailed analysis of effects of speed-reducing measures suggests that those studies have mostly concentrated on relationships between speed and the device height, spacing and speed midway between devices and have therefore not considered the effect of various traffic calming measures in sequence. Some useful insights into speed change prediction have been provided, but again, only individual measures were taken into account.

Furthermore, speed relationships, as a function of the distance, have been applied in the study of speed profiles of vehicles travelling along unimpeded roads, i.e. roads without traffic calming devices. The effect of speed control devices has been explained through a relationship describing the likely additional travel time imposed by their installation on local roads. Most of the reviewed models describing vehicle motion, were developed under time based relationships, mainly for acceleration (and deceleration), with velocity derived as a natural outcome of the acceleration modelling process.

With regard to this current investigation on the effects of traffic calming measures on speeds, the reviewed models do not seem totally applicable, firstly because of the nature of the relationships (acceleration-time and velocity-time), and also due to the characteristics of the roads involved in those studies (usually high speed environment) which differ from the ones under consideration. However, in the modelling development process, it seems advisable first to assess the applicability of those relationships already derived which appear more appropriate to this study. This will provide a starting point for the development of an empirical model based on the data collected. The most appropriate data will be vehicles' speed at different points along traffic calmed links, the type of vehicle, the type of driver, and the type, sequence and spacing of measures.

CHAPTER 4

DATA COLLECTION AND PROCESSING

The assessment of the impact of traffic calming measures on drivers' speed response was based on data collected on calmed roads in the City of York during the periods February to March and June to July 1994.

This chapter gives a description of data to be collected, the data collection system and the conduct of the surveys at the six selected sites in York. It also presents a description of the initial survey carried out on private University roads in Leeds to test some methods of speed measurement.

A brief explanation of the processes involved in the preparation of the data, the work demanded during data selection and data editing are also presented as well as the calculations performed to achieve vehicle speed at specific points along the links.

4.1 Survey Approach

Usually a traffic calming scheme has to go through many stages namely, planning, public consultation, funding and tender before it is implemented. Those stages are likely to provoke delays to the implementation of schemes.

Furthermore, the proposal of studying calmed sites by conducting before and after surveys was considered impractical as many factors especially budget constraints could affect the construction schedule, resulting in disruption to the study. Hence, in this current work, emphasis was given to the study of already implemented schemes to avoid disrupting the research due to the action of uncontrolled agents.

There are many types of traffic calming measures. Hodge (1992) presented a list of the frequency of incidence of measures. According to that list the most usual measures are: flat-topped tables, round-topped humps, raised junctions, pinch-points/narrowings, speed cushions and chicanes. Based on that list, which portrays the most likely situations to be encountered in traffic calmed roads, the survey approach has focused on the following measures: speed hump (flat and round topped), speed cushions and chicanes.

Ideally, according to the type of calming measures, they should be surveyed individually; in conjunction with the same measure (e.g. two speed humps); and in conjunction with different types (e.g. speed hump and chicane) performing as many combinations as possible. However, the study of individual traffic calming measures or even two combined measures has some implications in that in most of the cases measures are implemented in sequence. Arrangements of measures are frequently implemented to ensure average speeds over a length of road within a desired level.

Among the features prescribed by DoT in Traffic Advisory Leaflet 7/93 are gateways to indicate to drivers where the road changes in character, for example the start of a traffic calming scheme or at the entry of a speed limit zone. Aesthetically it is recommended that a range of measures is used rather than relying on one type of device. However, a large number of schemes are designed with only one type of measure (usually the cheapest one) as a result of budget constraints.

Traffic calming schemes are usually planned considering a sequence of measures. Hence, in the way schemes are being designed there will always be features such as gateways, traffic signs, or road markings to indicate to drivers the proximity of a speed controlled area. This has an implication in that the entry speed (upstream speed in relation to the first traffic calming measure of a sequence) will probably be affected by such features.

In view of the above, the survey approach needs to consider effects in sequence, as individual measures are very unlikely to be found since the actual emphasis is mostly on area-wide traffic calming rather than isolated road section treatments.

Moreover, the study of such effects will be restricted to a few combinations of measures due to time and manpower constraints.

4.2 Data to Be Collected

The main data to be collected is related to vehicles' speed as it is the best parameter that defines drivers' behaviour. It consists of the measurement of vehicle speed at predetermined points along traffic calmed links. Complementary data concerning the factors affecting speed were also to be collected and they were twofold: (a) constant data which correspond to road characteristics - width, length, types of control device, and (b) variable data on traffic flows and composition.

Data was to be collected on week days during off peak-hours when there is more likely to be free flow traffic and consequently less interaction between vehicles. The field work was to be carried out in daylight and where possible in good weather conditions in order to avoid variations in drivers' behaviour due to different weather conditions.

In addition to data concerning speed measurements at various points along a link mentioned above, downstream spot speed data was another requirement in order to assess whether drivers speed up after passing traffic calming devices as an attempt to recover the resultant time loss. It consists of the measurements of spot speed at a point further from a traffic calmed link.

4.3 Survey Methodology

Many techniques are available for the measurement of vehicle speed but few can easily provide this data at various points along a selected link. Considering the specific objective of obtaining speed profile data it was necessary to assess some methods in terms of advantages and drawbacks within the research objectives.

Usual methods for speed measurements comprise the use of radar meters, electronic timing using a pair of on-road detectors (such as treadle sensors, pneumatic tubes, optical sensors), and video recording methods (time-lapse photography and video-cassette).

A pilot test was designed in order to assess techniques related to ways of measuring speed at a series of pre-specified points on the road. This procedure has provided insight into the effectiveness of those techniques, as well as into difficulties and drawbacks that might arise whilst applying them. The experiment was devised to test the following equipment: a video recording camera, a radar speed meter (radar gun), a data logger (Environmental Computer), and an automatic traffic counter (Archer 400), the last two produced by Golden River Traffic.

4.3.1 The Clarendon Way Tests

The experiment was carried out on Clarendon Way, a road within the University grounds which is used as the main access to the Dental Hospital. It is a bus route, and presents low traffic flows of around 70 vph in one direction between 15:30 and 16:30.

In a first stage, an observer unnoticeable to the drivers and using a radar speed gun (MPH model K-15) recorded the speed of isolated vehicles as they passed by a specific point (P). At that time no road tubes had been placed. The second stage consisted of the placement of eight tubes on half of the carriageway. Then, speeds were again recorded using the radar gun. At this stage the Archer 400 was installed attached to a pair of tubes placed one metre apart in order to automatically register spot speeds. Figure 4.1 shows the layout and sensor numbers on Clarendon Way.

The adoption of the Environmental Computer for the automatic data collection involves the use of several pneumatic tubes, and the placement of those pneumatic tubes on the road raised the issue of whether they might influence drivers' behaviour. That concern is due to the fact that, generally for traffic counting purposes, only one or two tubes are placed on the road surface. Hence, an experiment was conducted to assess the impact of these tubes and associated equipment on drivers' behaviour and it is described in section 4.3.2.

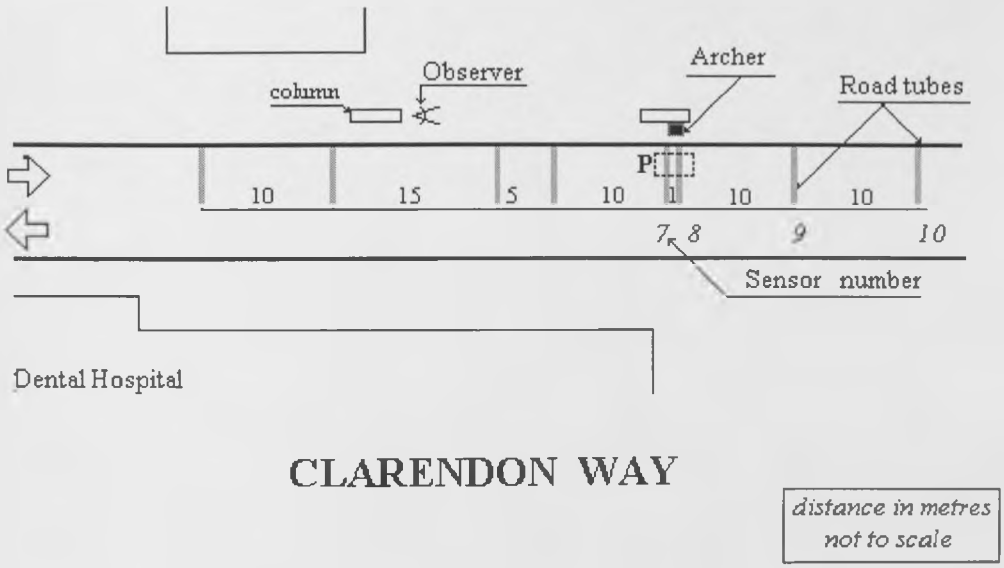


Figure 4.1: Layout of Clarendon Way Experiment

A description of each technique and its assessment during the experiments on Clarendon Way are presented next.

The Archer 400 Series Vehicle Classifier

The Archer 400 counts and classifies automatically road traffic passing over its sensors. The device uses two pneumatic road tubes which stretch across the traffic lanes. As a vehicle passes over the tubes, pulses of air are transmitted to the detectors situated in the Archer. It allows different configurations, for instance, vehicle classification only, spot speed measurement only, classification + speed, and traffic counter (single or two channels and directional counter).

This automatic counter records the selected data in time intervals, for instance, 5, 6, 15, 30, and 60 minutes. The recording capacity varies according to the configuration selected as well as to the intervals. The equipment was set up for recording only speeds in five minute intervals (the shortest interval available). The output presents speeds in a format of 12 bands. The minimum and maximum speed that will be recorded must be specified and for the test speeds thresholds were set up with a constant 3 mph increment. Hence, the output obtained was speed distribution in classes of 3 mph intervals.

Since the recorded observations are grouped in classes, it is not possible to calculate the mean speed of all observations. However, when the class intervals are small, the mean can be approximately calculated by considering the midpoint of each class as the actual observation.

This method of data collection proved to be very convenient as long as the work is totally automatic and it offers a wide choice of data analysis. Nevertheless, the biggest restriction to this equipment is related to the data format. It deals with population rather than with individual observations. In addition to this restriction, it is also difficult to obtain speeds at several points and impossible to trace individual vehicles.

Radar Speed Meter

The Radar Speed Meter was tested in order to verify the possibility of tracing speeds of vehicles as they are travelling along the course of a road.

The technique would be as follows: by using an audio tape, the marks shown on the radar display could be recorded as they actually change according to the car movement. This procedure would enable the construction of speed profiles at strategic points, previously marked on the kerb, by recording readings from different vehicles as they pass by those marks.

This technique would be valid for low traffic flows, when it is possible to trace a vehicle without the influence of following vehicles, which restricts its applicability. Another restriction is related to the misreading provoked by oncoming vehicles. This vehicle movement may interfere with the reading of the stalked vehicle on the meter. The same thing may happen when the stalked vehicle is being overtaken.

The above technique would be suitable only for specific conditions such as a one-way road (to avoid misreading) which presents low traffic flows or when only the speeds of isolated vehicles are recorded.

Video Camera

The use of a video camera was also assessed as a means of speed data collection. This technique might not provoke any influence on drivers' behaviour as long as it is placed out of drivers' sight. The main disadvantage is the time-consuming work of data transcription. Nevertheless, it enables the recording of a wide range of data, such as type of vehicle, traffic flows, conflicts, and unusual events.

Ideally, the video camera with a wide angle lens should be placed approximately 80 metres from the kerb in order to get a side view. This would enable a survey of 100 metres over a longitudinal section. Where it is not possible to fix it 80 m away, the placement of two cameras could sort out the problem and would demand a distance around 40m from the kerb. However, this procedure would result in more working hours to analyse the recorded images.

However, the cases described above are not compatible with the common housing pattern found along traffic calmed schemes which certainly hampers sight lines in such a lateral position. A vantage point would be a reasonable option, but it is rarely found at those sites.

The above situations have been checked at Gale Lane, Foxwood Lane and Clarendon Way, the latter in Leeds and the first two in York. All the cases have demonstrated the inadequacy of that technique due to the scarcity of a good point of observation. Hence, for this particular case, the video camera as the main data collection system was not recommended.

Environmental Computer

The Environmental Computer (EC) by Golden River is capable of recording passing time on 16 simultaneous channels. The data logger is one component of an automatic data collection system which works as follows:

- road tubes are placed on the road surface in order to send pulses of air each time a vehicle axle passes over it;
- the pulses of air are transformed into electric signals by air-switches;
- an input/output board receives the signals in 16 channels and sends them to the

data logger;

- the data logger is programmed to record those signals, but due to its small memory capacity it works connected to a computer;
- the computer is loaded with software which stores the recordings and decodes them in a readable binary format giving the number of the channel and the time the event has taken place; in this case, the time that the road tube is being crossed over by a vehicle axle.

In order to ensure that the data will be correctly analysed there must be a complementary record of unexpected events such as parked vehicles, overtaking, conflicts, incomplete journeys, and oncoming vehicles crossing over the tubes while driving on the right-hand side of the road. This might be done by recording onto a video cassette or by manual recording. Both cases require recordings synchronised to the data logger recording times in order to select the worthwhile data and to discard the useless ones. Consequently, this system requires the use of a video camera recording all the events or an observer with a synchronised watch to record unusual events.

Many operational problems arose during the Environmental Computer tests which were sorted out over the test days. Firstly, the main restriction to the system was related to power supply for the computer, the data logger and the air-switches. This problem was resolved by adopting a laptop instead of a PC which could be run on its own battery or connected to a car battery. The data logger runs on its own battery, but several voltage checks were made during the field test.

Secondly, the system was designed to fulfil the requirements of a previous survey using several metres of cable carried out a few years ago by Seco (1991). Such an amount of cables proved difficult to handle in the field. In this connection, a new system utilising ribbon cables to supersede the heavy ones was proposed for the actual surveys. This would enable some flexibility concerning the position of the boxes (air-switches) by sliding them over the ribbon and then easily placing them in the required position.

During the tests only four channels were used, that is, only four road tubes were connected to the data collection system, even though eight road tubes were available.

Data have been edited according to the following steps:

a) Tracing each vehicle individually, deleting disrupted recordings (e.g. incomplete journeys, influence of parked vehicles, vehicles travelling in wrong direction etc.). Complementary recordings, manual notes and video recordings, have proved to be very useful to edit data.

b) The use of a spreadsheet, in this case 'Quattro Pro', to calculate the following values:

b.1) spot speed obtained from the difference of passing times of the first axle over sensors 7 and 8, and also from the difference of passing times of the second axle over the same sensors. Those calculations have led to the values of spot speed on sensors 7 and 8 (sensors are shown in Figure 4.1);

b.2) the pair of tubes placed one metre apart, have also enabled the calculation of the vehicle wheelbase. This value has been calculated as the average of wheelbase values obtained from the difference of passing times of the first and second axles over sensor 7 and 8 multiplied by the spot speed;

b.3) spot speeds on the other single sensors have been calculated by dividing the wheelbase by the difference of passing times of the first and second axle over the sensor.

Despite only four channels being tested, the system demonstrated the capability of undertaking the desired task. It is adequate to the survey requirements although it is not the most convenient method because it demands many working hours in order to edit the recorded data since it records axles and not vehicle speed. However, part of this work can be automated.

There was some concern that for distances greater than 80 m, a loss of signals from the air-switches would occur. However, the connection layout gave indications of no signal losses over 80 m. Another test at the laboratory was carried out using ribbon cables of 100 m long and again no signal loss was detected.

4.3.2 The Influence of Road Tubes on Drivers' Behaviour

The experiment described here was also carried out at Clarendon Way using the tubes placed on the carriageway for the assessment of some data collection techniques as mentioned previously.

The experiment was carried out during two days without any tube on the road and for five more days after placing eight tubes on the road surface. The weather conditions were similar during the whole experiment. Speeds were measured (in mph) over one hour starting approximately at 15:15. The statistics of speed data obtained by using the radar gun are presented in Table 4.1. As can be seen, the means before and after are not similar.

Table 4.1: Speed Data Statistics - Clarendon Way

	Before	**After**	**18/02 Thur 15:15**	**19/02 Fri 15:15**	**22/02 Mon**	**23/02 Tue 15:20**	**24/02 Wed 15:30**	**25/02 Thur 15:40**	**26/02 Fri 15:10**	**03/03 Wed 15:35**
Cases	122	298	56	66	TUBES	55	69	63	49	62
Mean	26.06	23.14	26.68	25.53		21.25	21.82	24.27	24.69	23.90
StDv	5.88	6.65	5.54	6.11	placed	6.64	6.68	6.74	6.58	5.87
Min	12	12	12	15		12	13	12	12	12
Max	43	44	39	43	down	40	44	41	40	36

Therefore, the difference between the means of all speeds of both groups was studied in order to check if there is any significant difference between the average of speeds obtained from the sample representing the before situation (without tubes) and the sample representing the situation after placing the tubes. This analysis showed a significant difference between means at the 99% level of confidence as Table 4.2 shows.

Table 4.2: Difference Between Means (all days)

	mean speed (mph)	**cases**	**s**	**t**	**$t(0.025,\infty)$ $t(0.005,\infty)$**
without tubes	26.06	122	5.88	4.339	1.96
with tubes	23.14	298	6.65		2.58

Result of a similar experiment undertaken by Seco (1991) suggests that the tubes' influence is mostly concentrated on the first few days after their placement. Considering that this current study has presented lower means (approx. 21 mph) on the first two days after placing the tubes, another test of the difference between means was carried out. This time only the three last days have been computed, following Seco's suggestion.

This analysis showed a significant difference between means at the 95% but not at the 99% level of confidence, presented in Table 4.3.

Table 4.3: Difference Between Means (excluding two days)

	mean speed (mph)	**cases**	**s**	**t**	**$t(0.025,\infty)$ $t(0.005,\infty)$**
without tubes	26.06	122	5.88	2.468	1.96
with tubes	24.25	174	6.40		2.58

Johnston and Fraser (1983) when comparing driver behaviour in the presence and absence of visible detector systems - two treadle type sensor arrays spaced just under 300m apart - found no differences in speed between vehicles detected by conventional treadle sensors and those detected by "invisible" optical sensors.

Another study conducted by Pitcher (1989) analyses driver perception of a series of on-road treadle sensors. The conclusion that a large array of detectors has no effect on the behaviour of vehicle drivers in short residential streets was supported. The author emphasises that the conclusions were reached for a particular type of street which was characterised by a low speed environment and may not apply to other conditions.

In view of these results, it could be concluded that the tubes might influence drivers' behaviour mainly on the first days after their placement. Hence, some care must be taken in the decision of using several pneumatic tubes. The best procedure seems to be placing tubes down a few days before conducting the field work in order to get those drivers who regularly use the road used to possible changes to the environment. In addition to this, it is sensible to make the associated equipment as inconspicuous as possible during the field work.

4.3.3 Survey Method Adopted for Data Collection

In summary, considering the research requirements and the equipment available, the pilot tests have provided the following conclusions:

- The radar gun has demonstrated its weakness to trace speed of vehicles as they are travelling along a road.
- Although the automatic traffic counter (The Golden River 'Archer') has proved to be very convenient since the data collection is done automatically, its output format is not adequate for the research purposes because it deals with population and it is not possible to specify the speed measurements individually. Moreover, a separate device would be needed at each observation point.
- Video photography would be a good solution as long as it was possible to get a side view. This situation is unlikely to be encountered in built-up residential areas.

Hence, among the tested equipments, the Environmental Computer (plus associated equipment) is the most suitable for this study, despite not being the most convenient. In addition to data recorded automatically, complementary data (variable data) would also be required, especially for data editing. The considered approach was the use of observers in conjunction to a video camera. The conclusions above were drawn considering the data collection of speed profiles - measurement of speed at various points along a link.

The radar speed meter (radar gun) was adopted for the survey comprising the measurement of spot speed at points further from traffic calmed links. This data collection was conducted in two stages and involved spot speed measurements before and after the implementation of traffic calming schemes. This survey is fully explained later in this chapter.

4.4 Site selection

In the process of site selection a number of factors were considered. Among them, the situation to be studied played a very important role in conjunction with two other factors which are time and economic constraints and management problems. Moreover, it was essential to have representative traffic calming schemes which would fulfil the survey requirements yet enabling the data collection to be carried out from Leeds.

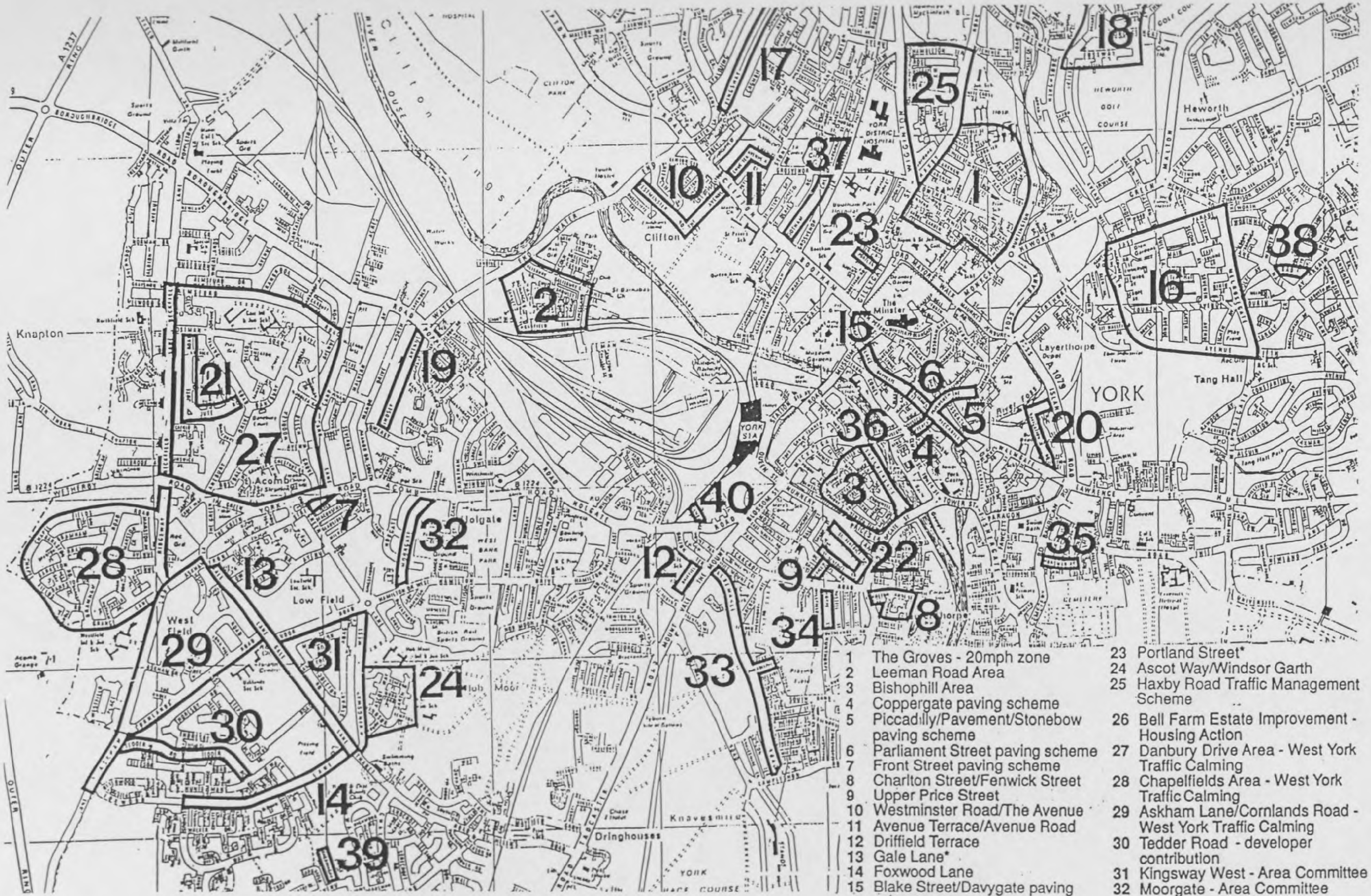
Under these considerations, the City of York was identified as a suitable place to undertake the field work. It offers a wide range of traffic calming techniques which represents a high number of potential survey sites. The extent of the York schemes is shown in Figure 4.2. In addition to this, York is 28 miles from Leeds which results in reasonable day trips for each survey day.

4.4.1 Potential Survey Sites

The site selection process and the definition of types of measure to be studied were issues considered together because they are strongly related and one could not be considered independently from the other. Firstly, only large traffic calmed areas such as Bishophill, The Groves and Gale Lane were considered for the field work.

In spite of being indicated as one of the top ten traffic calming schemes in Britain in a survey conducted by Hass-Klau et al (1992), the Bishophill Area was withdrawn from the first list in the light of the very low traffic flows observed in the area. The Groves Area is a 20 mph Zone and it presents a wide range of traffic calming measures. Within the area two one-way roads were identified as potential survey sites - Lowther Street and Penley's Grove Street/Townend Street which operate as a one-way pair.

The interest in using Gale Lane as a survey site has its origin in the idea of also studying traffic redistribution resulting from the introduction of traffic calming schemes. The construction schedule would have allowed before and after studies for that purpose. In this connection Foxwood Lane was also included in the first list of roads.



1	The Groves - 20mph zone
2	Leeman Road Area
3	Bishophill Area
4	Coppergate paving scheme
5	Piccadilly/Pavement/Stonebow paving scheme
6	Parliament Street paving scheme
7	Front Street paving scheme
8	Charlton Street/Fenwick Street
9	Upper Price Street
10	Westminster Road/The Avenue
11	Avenue Terrace/Avenue Road
12	Driffield Terrace
13	Gale Lane*
14	Foxwood Lane
15	Blake Street/Davygate paving scheme
16	Tang Hall (West) area
17	Kingsway North
18	Muncaster area
19	Lindsey Avenue
20	Navigation Road
21	Jute Road
22	St Benedicts Road
23	Portland Street*
24	Ascot Way/Windsor Garth
25	Haxby Road Traffic Management Scheme
27	Danbury Drive Area - West York Traffic Calming
28	Chapelfields Area - West York Traffic Calming
29	Askham Lane/Cornlands Road - West York Traffic Calming
30	Tedder Road - developer contribution
31	Kingsway West - Area Committee
32	Moorgate - Area Committee
33	Albermarle Road
34	Thorpe St
35	Horsman Avenue
36	Skeldergate
37	Bootham Crescent
38	Bad Bargain Lane
39	Sherringham Drive
40	Cambridge Street

Figure 4.2: Map of Traffic Calming Schemes in York

At this stage the proposed survey sites comprised the following types of measures: speed humps, speed cushions, chicanes and speed tables (raised junctions).

The survey sites were chosen in order to strike a balance between sites and measures to be considered for the stages of calibration and validation of the model. Livingstone Street in the Leeman Road Area, which presents two chicanes in sequence, was added to the list of sites to keep the balance referred to above. Table 4.4 presents the first proposal of survey sites as well as types of measures.

The sites have been categorised as calibration and validation sites in order to develop a model which accounts for variations in speed profiles according to the type and position of measures within a sequence. This process has involved two distinct stages and two distinct sets of data being obtained from sites categorised as either calibration or validation. The first set of data has been used to produce a model which has been validated using the other set of data by comparing the modelled and the measured situation.

After the pilot survey conducted at Livingstone Street and described later in this chapter, it was decided, as far as possible, to avoid surveys in roads with traffic volume greater than 350 veh/h experienced at that site. For this reason, Lowther Street was discarded for the actual survey. Therefore, some adjustments had to be done to the list in order to replace Lowther Street and keep the balance between sites for calibration and validation.

This new search for sites led to two large traffic calming areas: Muncaster and Tang Hall. Monkton Road in the Muncaster Area has a sequence of different measures, but its low traffic flows and many incomplete journeys to local shops made it infeasible since it would demand extra days of field work in order to obtain the required sample.

Table 4.4 :Proposed survey sites - Type of Measures and Categorisation

LIVINGSTONE ST	FOXWOOD LN	GALE LANE	TOWNEND ST	LOWTHER ST
junction	cushion	...	junction	junction
chicane (*)	cushion (*)	cushion	hump	hump (*)
chicane (*)	hump (flat top) (*)	cushion (*)	table	table (*)
junction	hump (round top) (*)	cushion (*)	hump (**)	chicane (*)
	...	cushion (*)	table (**)	chicane
	cushion (**)	cushion	chicane (**)	table (*)
	cushion (**)	cushion + island	chicane	hump (*)
	cushion (**)	...	hump	hump (*)
	cushion		junction	junction
	mini roundabout			

Key: (*) calibration; (**) validation.

Fourth Avenue in the Tang Hall Area presents traffic flow below 100 vehicles per hour per direction and it would demand at least an extra day of data collection compared to the other sites. However, it was the most attractive site among those featuring a flat-topped speed hump. Conducting surveys on low traffic flow roads would represent an increase of working days and hours per day and consequently, the road tubes would stay longer on the road (which is not advisable); it would demand more journeys to York extending the field work schedule; and in addition to the problem of extra power supply for the extra hours of data collection, this would probably happen during evening peak-hours which were avoided at all sites. Table 4.5 shows the resulting sites for the data collection as well as type of measures and categorisation.

4.5 Survey Preparation

In the process of the survey preparation some aspects were taken into account before proceeding with the field work. The primary guideline to the survey design was the equipment performance in terms of its maximum operation distance without signal losses. Therefore, the decision about cable length was made in consideration of the following factors:

- generally traffic calming measures are implemented within distances which vary from 60 to 80 m;
- it was necessary to position tubes within a reasonable distance between measures in order to obtain suitable speed profile curves;
- the cable should be arranged in two arrays to enable the use of 16 channels (each of two arrays containing eight sensors) and bearing in mind that the survey vehicle ought to be placed in the middle of the link.

Hence, cables of 100 m long were adopted that could cover maximum links of 200 m long, thus enabling the survey of three consecutive measures at a time.

Table 4.5: Actual survey sites - Type of Measures and Categorisation

LIVINGSTONE ST	FOXWOOD LN	GALE LANE	FOURTH AV	TOWNEND ST
junction	cushion	...	...	junction
chicane (*)	cushion (*)	cushion	cushion	hump
chicane (*)	hump flat top (*)	cushion (**)	cushion	table
junction	hump round top (*)	cushion (**)	cushion (**)	hump
	...	cushion (**)	hump round top (**)	table
	cushion (*)	cushion	hump flat top (**)	chicane (**)
	cushion (*)	cushion + island	hump flat top	chicane (**)
	cushion (*)	...	cushion	hump (*)
	cushion		junction	junction
	mini roundabout			

Key: (*) calibration; (**) validation.

Some other aspects related to site characteristics demanded preliminary visits to the sites to get some measurements in order to define tube positions, the place to park the survey vehicle, the observers' position, the best place to install the video camera, and also to estimate the required material (length of tubes, nails and cleats).

Such specific characteristics inherent to each site demanded a different survey design concerning tube position and the strategy to cope with those particularities. The variation in the survey design as well as site characteristics are described later in this chapter.

4.5.1 Personnel

Personnel was one factor which had guided the survey towards a simple design in order to cope with unavailability of staff, while achieving high quality data.

The process of preparing the survey sites in terms of placing tubes on the road and setting up the automatic data collection system required the support of two technicians from the Civil Engineering Department at Leeds University. Data collection itself required two observers to complement data collected automatically.

4.5.2 Automatic Data Collection System

The automatic system of recording events is based on a data logger computer working together with a portable computer and connected to 16 automatic sensors through 16 input channels. The arrangement of the system consists of the following elements.

Automatic sensors

The sensors consist of pneumatic tubes each connected to an air-switch. Tubes were fixed onto the road by cleats which were nailed into the asphalt. The short periods of data collection offered the possibility of using "D" profile tubes glued onto the road which would certainly have made the task of placing tubes a lot easier and more flexible. However, this option was discarded since it requires a dry surface and it was very unlikely to have dry conditions during all days of data collection. Therefore, "O" profile tubes were preferred to "D" profile ones as they are cheaper and they would conform with the task.

Network for Data Collection

The network consists of nodes (boxes) and links (cables). The main cable is a ribbon type with up to 8 parallel connections. In order to have 16 sensors it was necessary to use two arrays of ribbon cable each one with 8 nodes (boxes and sensors) and 100 m long.

The nodes are formed by 16 identical waterproof boxes and each one contains one air-switch which transforms the air impulse generated on the tube into an electrical signal. Each node (air-switch box) is connected to the network through a waterproof connector: a small black box clipped on to the main cable (ribbon) shown in Figure 4.3. The adoption of those black boxes has allowed some flexibility to change the position of the connections according to the distance between tubes for each site. This could be easily done by removing the connections and replacing them by wire connectors.

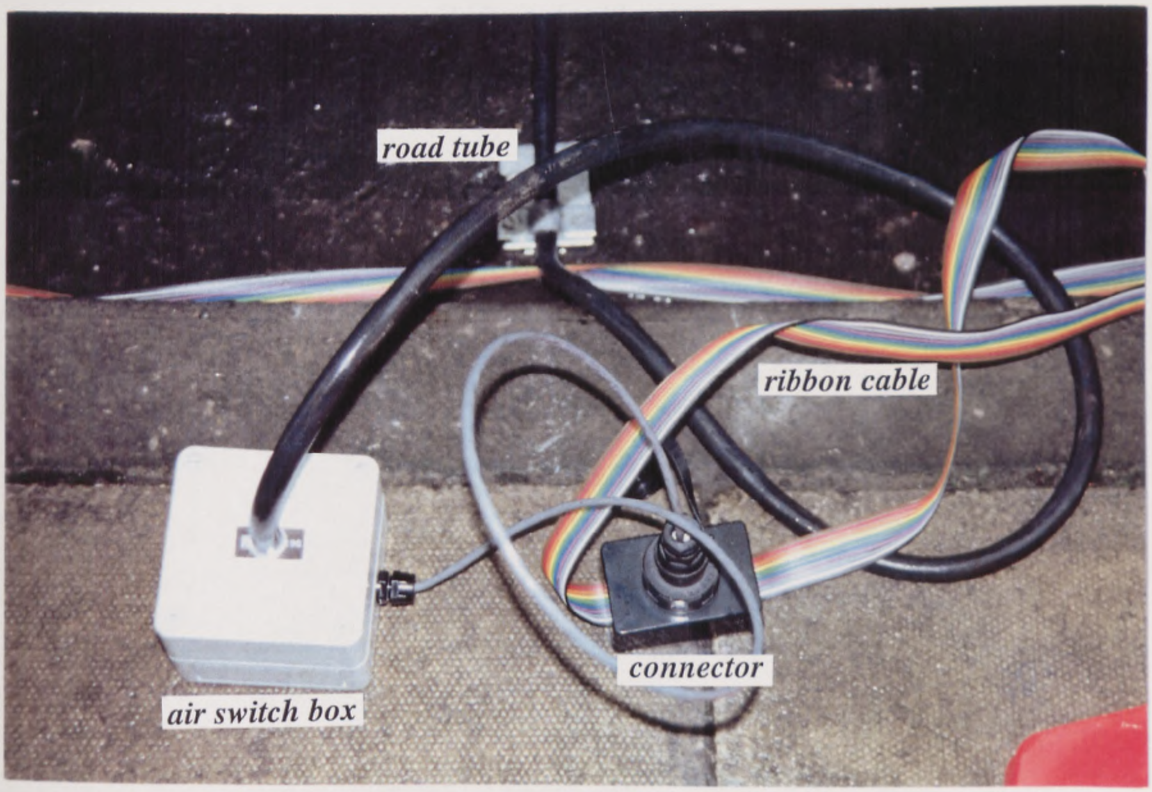


Figure 4.3: Automatic Sensor Connections

The I/O Port is a simple electrical device which compiles all the 16 output channels assembled into two groups of eight plus two for the power. Each of the groups (channels 1 to 8 and 9 to 16) is connected to one I/O port provided on the data logger. A diagram is shown in Figure 4.4.

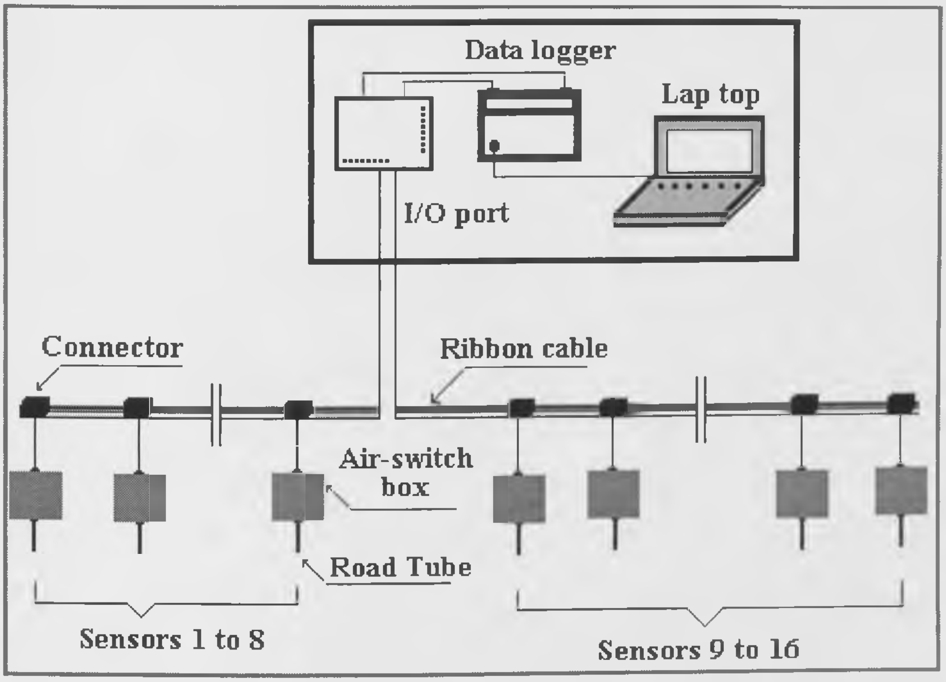


Figure 4.4: System Structure Diagram

Data Logger, Software and Computer

The Environmental Computer is designed for outdoor applications and it was used with its own battery. The built-in software records the passing times with a step size of 1/600 of a second. It was connected to a portable micro computer Phillips LTP 3230. The portable was preferred to any other micro computer because it could be run on its own battery or be connected to other sources of power supply such as a car battery via the survey car cigarette lighter or to a spare car battery.

The portable micro computer was essential to store the information received from the data logger and at the same time to test whether the sensors were working properly. The software used on the portable was written by Dr David Lear at Nottingham University. Once the communications between the portable and the data logger are established the data collection process can be performed. The data logger receives the inputs of each sensor and checks the time on the clock. A pair of data (number of sensor + time) is stored and a binary file is created in the portable.

4.5.3 Complementary Data Recordings

The need to collect complementary data resulted from the fact that the Environmental Computer records vehicle axle passing time rather than vehicle speed.

Information about the type of vehicle was essential to data handling. The vehicle entry time in the link was another piece of important information as the events were recorded by their occurrence time plus the sensor number. The task of tracking individual vehicles required information on the occurrence of conflicts (whatever the agent i.e. another vehicle, cyclist or pedestrian), turning movements onto and off the road and incomplete journeys.
The recording of events above were twofold:

Manual Recordings

This approach consisted of an observer with a stop watch writing down on a prepared form the time a vehicle entered the link (sensor number one was considered the link entry) and the type of vehicle. This observer also recorded unusual events related to that vehicle.

Video Camera Recordings

This approach was necessary because an observer could not cope with the surveillance of the whole link especially for traffic flows over 150 veh/h. Ideally the video camera should have been able to survey the whole link. However, due to characteristics of the local environment it was not possible to get a vantage point. As a result the video camera was installed so that it would survey the link section not covered by the first observer. Since the camera was fixed on a tripod there was a need for another observer to stand by it. This second observer had a specific function of reporting the facts occurring at that link section out of the first observer's sight while monitoring the camera. Those comments were also recorded by the built-in camera microphone.

Data logger, stop watches and video camera were used synchronised in order to get consistent sets of data.

4.5.4 Liaison with York City Council

During the development of this research, liaison with York City Council has been established in order to obtain the permission to carry out "works" in the Public Highway as well as to gain access to very useful information.

York City Council provided information about its overall traffic calming policies which were of great help in the process of site selection. Essential data were also provided concerning spot speed surveys conducted before the implementation of traffic calming schemes. It was possible to obtain data related to traffic counting for the before and after situation for some sites.

Another important aspect resulting from this liaison was the access to traffic calming projects which included all details about the schemes such as type of measures and position on the road. This information facilitated the survey design in that it reduced the number of road visits as well as road measurements.

4.6 Pilot Survey - Livingstone Street

Ideally the pilot survey should had been undertaken soon after the initial survey. Nevertheless, delays were experienced and consequently it had to be postponed. In view of this, Livingstone St was used as a pilot test as well as for the actual data collection.

4.6.1 The Site

Livingstone Street is a one-way road located in the Leeman Road Area of York. It is still being used as a through route even after the implementation of calming measures. As part of the scheme two chicanes were constructed on Livingstone St. The road segment surveyed is about 180m long and presents three major junctions in addition to two minor ones. Traffic flows observed during survey hours were around 360 veh/h.

4.6.2 The Survey

On the 27th January 1994 (Thursday) 16 pneumatic tubes were placed on the road. The position of the tubes were slightly different from the layout prepared at the office to cope with the junction radii and narrow entrances. The tubes were fastened at both ends and where the road width was greater than 4.5 m tubes were also fastened in the middle to keep them in position. The road lay-out and tube position are presented in Figure 4.5.

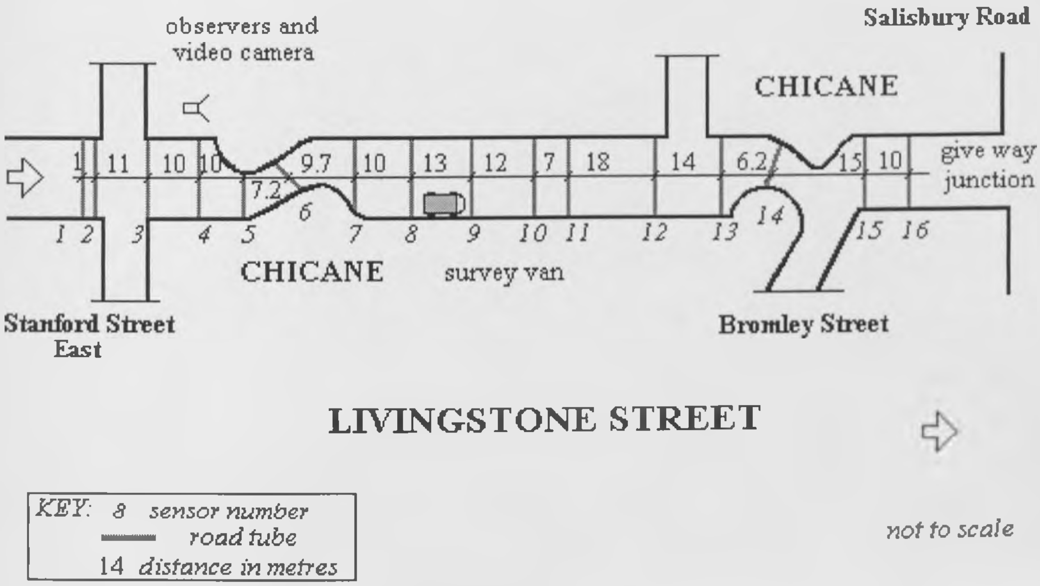


Figure 4.5: Livingstone Street - Layout and tubes position

The automatic data collection system was set up on the following Monday (31st January) for the first test involving the use of all 16 channels. The cables (ribbon) were laid down along the kerb and the black boxes (which connect the air-switches) were then clipped on to the cable according to the tubes distance. The next step consisted of connecting the grey boxes (which contain the air-switches) to the black ones through the cable provided. The two boxes and the connection cable were hidden under plastic cones which were laid over the pavement. Plastic cones were used in order to warn pedestrians of any possible hazards due to presence of boxes over the pavement and cables along the kerb.

As it was the first on-road trial of the complete automatic system it took a few hours from the setting up till the first successful run and some considerable checking of the connections and sensors. Therefore, data collection was carried out over just half an hour from 15:20 to 15:50. Data collected on this day were not considered for the analysis.

A video camera was used to collect complementary data. Since it could not survey the whole link, the camera was installed on a tripod so as to enable the surveillance of the busiest part of the road, from tube 7 up to tube 16.

In the process of manually recording events there was an observer writing down the events at the beginning of the link, especially entry time and type of vehicle as well as any cars turning off or onto the road at the first junction. Another observer was writing down odd events occurring out of sight of the first observer. A third observer was standing by the camera. Meantime the technicians were inside the survey car in charge of the data logger and the laptop.

After the data collection session all the equipment was removed apart from the tubes which were left on the road.

4.6.3 Lessons from the Pilot Survey

The first trial of the automatic data collection system pointed out positive and negative elements. The latter were to be avoided in the next surveys as far as possible, whilst the positive elements remained.

The main difficulties encountered at Livingstone Street were:

1) The first pair of tubes (one metre apart) were placed in front of a Post Office. A high demand for parking space in this area was observed. Therefore manoeuvres over those tubes were frequent.

2) The last two tubes (15 and 16) were placed near the junction where queues were likely to build up while vehicles are negotiating the give way junction.

3) Tubes 6 and 14 were placed mid-way within each chicane and they were prone to send four signals for each vehicle, instead of two signals, one for each axle, as each wheel crossed the tube at a different time.

4) High traffic volume made it difficult to register all the unusual events.

5) The existence of junctions along the link allowed exits without crossing over all tubes.

6) The video camera could not be installed in a place that would have enabled the surveillance of the whole link. In view of this the events at the link entrance were manually recorded and this proved difficult to cope with under heavy traffic conditions.

Despite having undertaken initial tests at the University grounds, the equipment presented more complexities concerning its use and data handling. Table 4.6 presents the main differences experienced in the initial survey at the University grounds and the pilot survey in York.

Table 4.6: Comparison between initial and pilot survey

	Initial Survey Clarendon Way	**Pilot Survey Livingstone Street**
Number of sensors	04	16
Traffic Volume	~ 70 vph	~ 360 vph
Video camera	the whole link	part of the link
Observer	in a vantage point	on the road
Amount of data	small: easy to handle	huge: complex to handle

Some lessons were learnt from this survey and were guidelines for the other sites. Consequently, the following points were sought during the survey design:

- select links with few or no junctions at all;
- survey timing out of peak-hours in busy roads;
- to avoid junctions where queues were likely to build;

- the pair of tubes (one metre apart) which identifies the vehicle entry in a link should not be placed before a junction where there are likely to be a considerable number of vehicles turning off the road resulting in recording useless events;
- the use of a video camera was highly beneficial since it recorded events likely to be missed by manually recording. Furthermore, the built-in microphone was very useful to record spoken comments made on the occurrence of events that could go unnoticed while playing back the tape since the traffic stream could block the observer's view.
- two observers were capable of coping with the amount of complementary data to be recorded (manually or orally).

4.7 Field Survey

4.7.1 Livingstone Street

In spite of the lessons from the previous day only slight adaptations were made in consideration to the difficulties faced and they referred basically to the way of collecting complementary data. On the other hand, as little could be done about the complications caused by road layout, it made the survey team more aware of the problems, and therefore more prepared for the task.

The actual data collection occurred on the following day 1st February (Tuesday) and the amount of time required to set up the equipment was less than the first day as the black boxes were already connected to the main cable. However, it was still necessary to lay the cables down and to connect the air-switch boxes to the main cable.

The weather did not cooperate and it only allowed around one hour of data collection from 11:35 to 12:45. Also an unexpected event caused disruption to data collection as a truck parking at the end of link crossed over the pavement smashing one black box and also cutting the cable off. Hence, from 12:00 onwards data from sensor number 15 was not recorded. This was only noticed after ending that survey period. The cable could be repaired on site. However, the survey could not be carried on as the weather conditions worsened.

On the 3rd February (Thursday), the equipment was easily prepared and the survey started at 9:30. At this time the road was not as busy as the previous days and traffic streams run almost freely and the observed headways were more appropriate to the research purpose. It was expected to conduct the survey over a longer period but, again the weather got worse (hail and snow) making it impossible to carry on the survey.

The last survey day took place on the 10th February (Thursday). The weather was fine and data collection progressed normally from 10:00 to 13:00. Tubes were removed from the road.

Figure 4.6: Experiment conducted at Livingstone Street (towards Salisbury Rd)

4.7.2 Foxwood Lane East

Foxwood Lane is a two-way local distributor road within a residential area and it presents hourly traffic flows around 150 vehicles per direction. It is a link to two local distributors, Gale Lane and Askham Road. Two sections of the road were selected for the survey. The first section is from Huntsman Walk to Gale Lane and it comprises a sequence of three speed cushions. The array of 16 tubes were placed on 11th March (Friday) as shown in Figure 4.7.

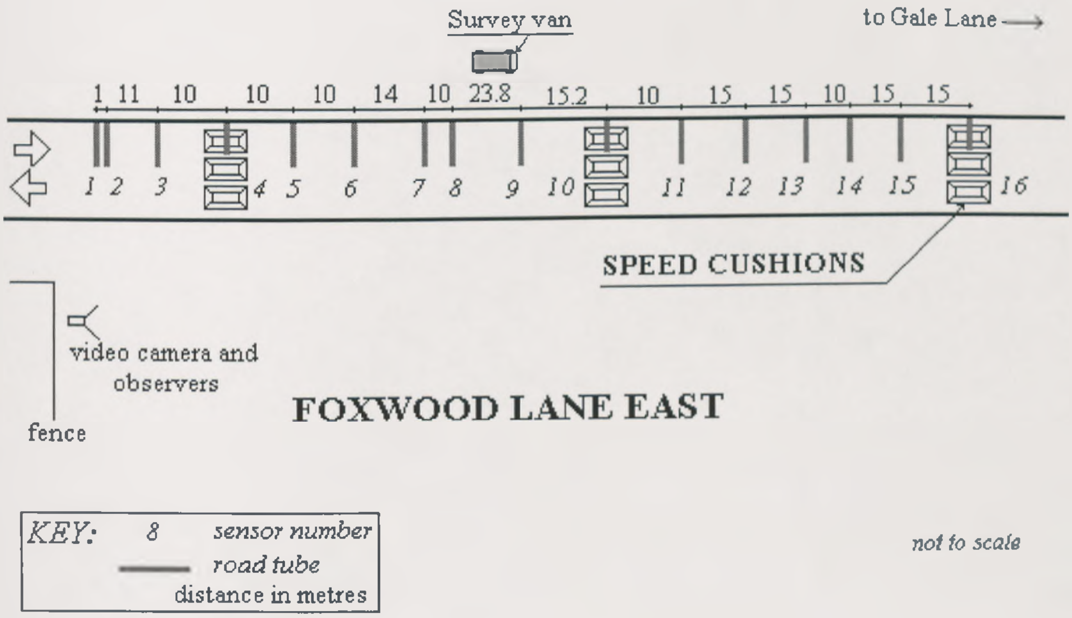


Figure 4.7: Foxwood Lane East - Lay-out and tubes position

On the first day of data collection, which took place on the 15th March, from 10:45 to 13:00, a few tubes had to be replaced due to damage caused by traffic mainly to those tubes over the cushions which required two more cleats each to keep them in place and in the same shape as the cushions. Apart from that, the survey was carried out without problems.

The survey van was parked on the verge and no restrictions to pedestrian movements or to vehicular traffic were noticed.

The second survey day took place on the 18th March (Friday) from 10:00 to 12:00. As usual, data collected was examined after ending the survey session while the equipment was still on the road. Since the amount of data was satisfactory, the tubes were removed that same day.

In spite of being easy to record complementary data manually due to lower traffic volumes, the video camera was also used since it could be useful to check events and also during the task of data editing.

Figure 4.8: Experiment Conducted at Foxwood Lane East (towards Gale Lane)

4.7.3 Foxwood Lane West

This section comprises two speed humps, the first one is a round top and the following a flat top built to be used as a pedestrian crossing, and the next measure is a set of three speed cushions.

Tubes were placed on the 22nd March and the survey was carried out on the 25th March (Friday), 28th March (Monday) and on the 30th March (Wednesday). Figure 4.9 presents the road lay-out and the tube position.

Data collection was not as easy as that experienced at Foxwood Lane East. There are some traffic disturbances caused by parking, the bus stop and the junction near the end of the section. In addition to this many cars were turning off the road in order to get access to shops around the corner and therefore they did not complete the journey throughout the link. The survey van was again parked over the verge otherwise it would disturb traffic as there was no sheltered parking space in the midlink.

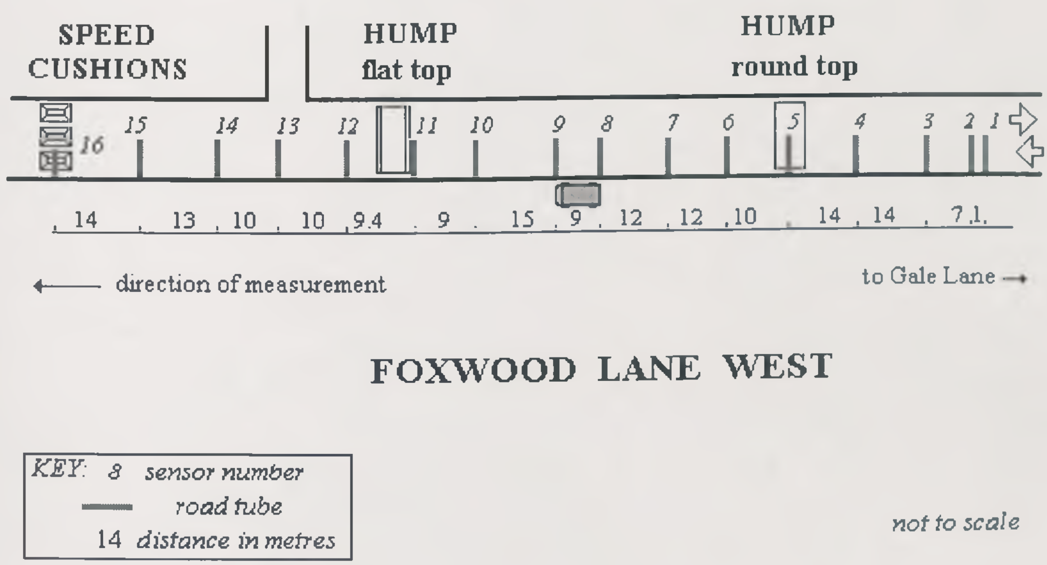


Figure 4.9: Foxwood Lane West - Layout and tubes position

The type of housing and also the features along the road (shops, bus shelter, and bus stops) did not favour a good position for the video camera. Therefore, also due to weather conditions (cold and sometimes drizzle) the video camera and the observers were positioned inside the survey van.

Figure 4.10: Experiment Conducted at Foxwood Lane West (towards Askham Lane) showing a typical conflict situation

4.7.4 Townend Street

Townend Street is a one-way road within The Groves Area which has been traffic calmed as a 20 mph Zone. This road presents a variety of calming measures such as raised junctions, chicanes, round topped humps and road narrowings.

The surveyed section comprises two chicanes and a round topped hump in this sequence. Tubes were placed on the 23rd June (Thursday) and the survey was carried out on the 27th and 28th June. Data were collected over 3 hours each day. The road layout is shown in Figure 4.11. The survey van was parked on a proper parking bay and the observers and the video camera were positioned on the opposite side of the road.

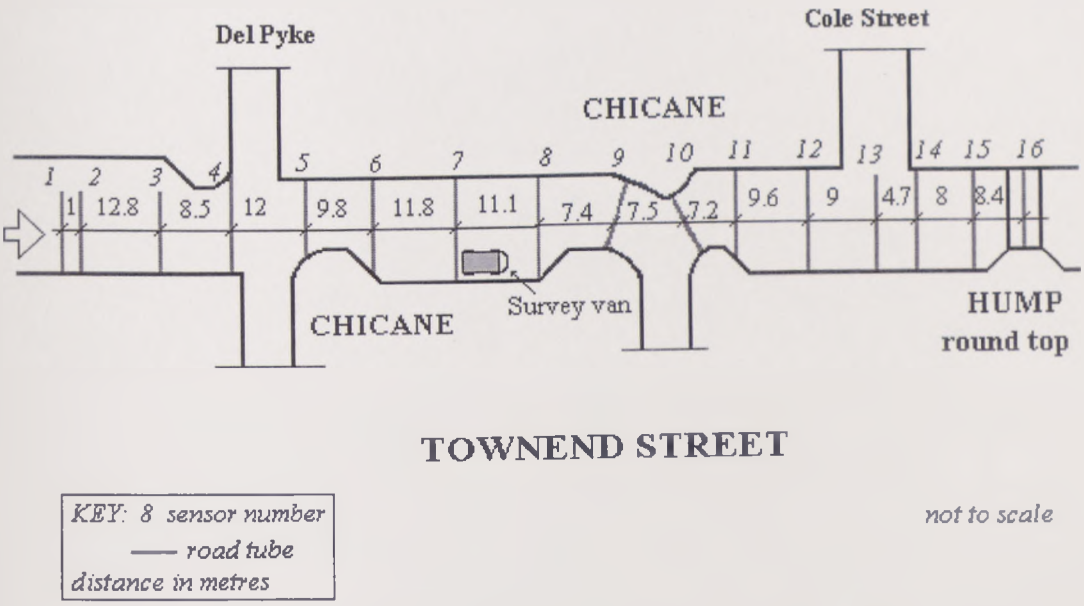


Figure 4.11: Townend Street - Layout and tubes position

Figure 4.12: Experiment conducted at Townend Street

During the data collection an operational problem arose causing disruption to part of the data stored. The problem source was the low power supply that was not feeding the computer properly. This might have happened as a result of the computer battery pack not storing enough power to allow four hours of work. Another operational problem also caused disruption to data when the cable was cut off by a car crossing over it at the junction. Although the cable was protected by a rubber cover, it was prone to that because of the many fragile connectors used to join the wires after removing the black boxes. This incident resulted in the loss of signals to sensors 10 to 16. Apart from those problems which took some time to be identified and corrected, the data collection progressed well.

4.7.5 Gale Lane

Gale Lane is a busy secondary road located in the West York area. It is a two way road which has been recently traffic calmed with a series of speed cushions, some have been combined with traffic islands to provide for pedestrians crossing. The land use is mostly residential and some local shops are scattered along the road. The surveyed link comprises three sets of speed cushions between Tudor Road and Danesfort Avenue junctions. Tubes were placed there on the 27th June and data collection took place on the 30th June and the 1st July over 3 hours each day. Figure 4.13 shows the road lay-out and the position of the road tubes

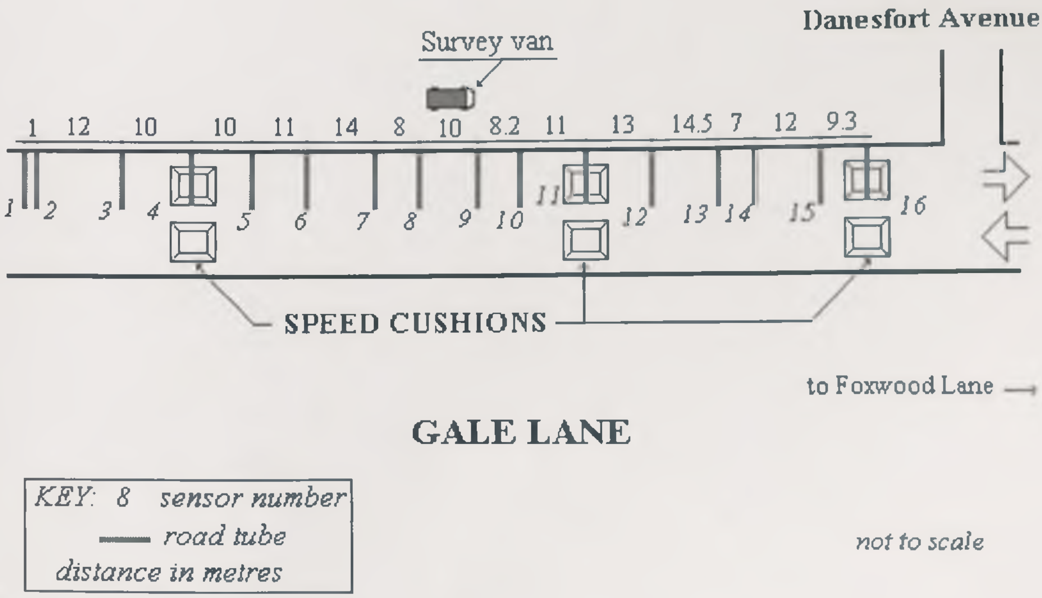


Figure 4.13: Gale Lane - Layout and tubes position

In order to avoid problems resulting from the poor computer power supply, at the first sign of low battery the laptop was connected to the survey van via the cigarette lighter. The observers and the video camera were placed inside the van which was again parked over the grass verge as the road has a double yellow line along that link. Having the observers inside the van proved very useful since any problem concerning the power supply could be easily detected and shortly repaired.

Figure 4.14: Experiment conducted at Gale Lane

4.7.6 Fourth Avenue

Fourth Avenue is a two-way residential road within Tang Hall area. Near Melrose Avenue there are local shops on both sides of the road and two flat-topped speed humps were built to be used as pedestrian crossings.

The surveyed link comprises a flat-topped hump, a round-topped hump and a set of speed cushions in this sequence. The road layout and tubes position is presented in Figure 4.15.

Within the link there are two minor junctions and the ribbon cable was placed down along these junctions. As a result, the same problem of the cable being cut off (as during Townend Street experiment) by a vehicle crossing over it was faced again. Nevertheless, after the lesson from Townend Street many voltage checks were periodically done during the data collection in order to avoid the loss of as small a portion of data as possible. Therefore, whenever the problem occurred (and it did occur quite a few times) it was easily detected and repaired.

Tubes were placed on the 4th July and the data collection was conducted during three days on the 6th, 7th and 8th July. Low traffic flows experienced at this site resulted in extensive data collection periods

The survey van was parked over the pavement in order to avoid road traffic blockage. The Gale Lane strategy was adopted and the observers stayed inside the van monitoring the power supply. Complementary data recording could easily be done manually due to the low traffic stream and therefore, the video camera was not used.

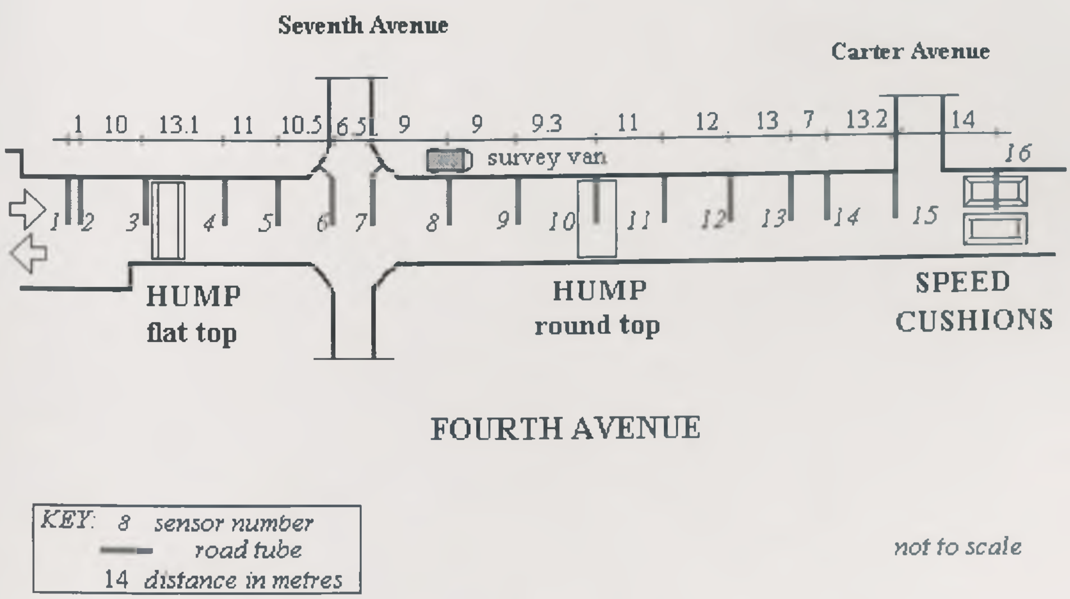


Figure 4.15: Fourth Avenue - Layout and tubes position

The bus stop near the first pair of tubes caused a lot of disruption to the data collection. Queues were formed whenever a bus stopped there and vehicles overtaking the bus certainly missed the first pair of tubes if not others as well. Other factors which contributed to data disruption were parking manoeuvres in front of the shops and also loading and unloading vehicles parked in the traffic lane obstructing the traffic.

Figure 4.16: Experiment conducted at Fourth Avenue

There was no possibility of avoiding those problems as they are typical consequences of road traffic and use. In this regard, data collected under those conditions were only considered in the sample if they complied with the data selection criteria established for this study (criteria are fully explained in Section 4.9.1). Therefore, extra periods of data collection were needed to achieve the sample requirements.

Table 4.7 presents a summary of the data collection timetable for all the six sites. It contains dates on the tubes placement, days and periods of data collection.

Table 4.7: Data Collection Timetable

SITES	TUBES PLACED	DATA COLLECTION	
		DAY	PERIOD
LIVINGSTONE STREET	27/01 (Thur)	01/02 (Tue)	11:30 to 12:45
		03/02 (Thur)	9:30 to 12:50
		10/02 (Thur)	10:00 to 12:15
FOXWOOD LANE EAST	11/03 (Fri)	15/03 (Tue)	10:45 to 13:00
		18/03 (Fri)	10:00 to 12:00
FOXWOOD LANE WEST	22/03 (Tue)	25/03 (Fri)	10:00 to 12:10
		28/03 (Mon)	10:00 to 13:00
		30/03 (Wed)	10:00 to 14:30
TOWNEND STREET	23/06 (Thur)	27/06 (Mon)	11:00 to 14:00
		28/06 (Tue)	10:00 to 14:30
GALE LANE	27/06 (Mon)	30/06 (Thur)	10:15 to 13:35
		01/07 (Fri)	9:50 to 12:00
FOURTH AVENUE	04/07 (Mon)	06/07 (Wed)	10:30 to 15:10
		07/07 (Thur)	10:00 to 16:00
		08/07 (Fri)	10:00 to 13:00

4.8 Data Selection

4.8.1 Criteria for Data Selection

Firstly, it is important to introduce two essential definitions used as a basis for the data selection which was observed throughout this study. The first one is related to the type of vehicle and the second one to the traffic flow condition.

Since the target vehicles were restricted to those which are typical of a traffic calmed road, only cars and light goods vehicles (vans) were considered in the sample while buses, coaches and other goods vehicles were excluded. For the purpose of this study, the term

van is being applied to all light goods vehicles except lorries according to the UK Department of Transport (1987) classification.

As this study is an investigation of drivers' behaviour when they are negotiating calming measures, it is reasonable to study behaviour when a driver has absolute control over the decision about his/her driving style without being pressured by other vehicles. A vehicle travelling under these conditions has been termed an **unimpeded vehicle**, which implies that the driver is not being affected by the motion of the vehicle immediately preceding him/her in the traffic stream, or by other agents (pedestrians, cyclists and opposing vehicles).

In the light of these definitions, the following criteria were established to select data for editing, so that in these situations data were removed:

- vehicles starting or stopping within the street section;
- vehicles others than cars or vans;
- vehicles' behaviour affected by pedestrians, cyclists or animals;
- conflicts between opposing vehicles; and
- incomplete data.

The minimum gap to determine whether a car that is being followed is affecting speed was determined for each site and it was considered as the headway which allows a spacing equal to the distance between traffic calming measures along the link for speeds within 20 - 25 mph. Table 4.8 presents the measured headway values which were adopted during the process of data selection as a result of an adjustment between calculated and on-road measured headways.

Table 4.8 : Headway values adopted for data selection

Sites	Livingstone St	Foxwood Ln West	Fourth Av	Townend St	Foxwood Ln East	Gale Ln
Headway (sec)	7.0	7.0	7.0	6.0	6.0	6.0

4.8.2 Data Selection Routine

Some vehicles which seemed to comply with all criteria could be selected on site. The others were selected after detailed video analysis. Actually, the completion of the data selection process only occurred after examining the decoded files when the following circumstances were detected: incomplete data (vehicles missing road tubes or equipment failure), disrupted data and minimum headway between vehicles kept along the whole link.

The decoded files were obtained using the Decode.C program developed at Nottingham University. The original program has been altered to provide also an output of time in the conventional format (hh:mm:ss:ms) in addition to the number of sensor and the time in seconds. This additional output was extremely useful to match the events recorded manually and by the video camera.

The possibility of tackling data selection automatically was discarded initially, because it would demand expertise in programming, especially because of the many different conditions and restrictions to impose in each link in regard to turnings off and onto the link, incomplete journeys, overtaking and other events. Secondly, the program would require the precise event time occurrence input to identify those situations in the files generated by the data logger and then proceeding with the applicable data deletions. Furthermore, such precise time information would demand browsing files since it could not rely on the manual notes because they were not recorded with the same precision as those in the data logger. Therefore, since the identification of those disrupted data would have had to be done anyway, the manual sample selection was preferred.

4.9 Data Processing

The process of editing the large files generated by 16 simultaneous sensors has demanded the use of a powerful spreadsheet to cope with such dimension. Therefore, 'Excel' was chosen to perform data reduction.

Grouping and organising data files by individual vehicles was done through a program written in Pascal (Clas.pas). The new database format has designated one line to each vehicle rather than having two columns format (channel and passing time). In so doing, it has facilitated the calculations in the spreadsheet. The program has also assisted in checking for mistakes made during data editing, by computing the total of vehicles sorted and the total number of events by channel. 32 events (2 times 16 channels) are expected for each selected vehicle and hence any number not a multiple of 16 represented the occurrence of an editing error.

4.9.1 Speed Profiles Calculation

Road tubes layout varied from road to road but the first pair of tubes at the entrance of the link were always placed one metre apart. Passing time data obtained from this pair of tubes were crucial to determine the distance between axles of vehicles (wheelbase). A spacing of 1 metre was adopted in order to reduce the possibility of vehicles accelerating or decelerating in between the tubes. The calculation of the wheelbase is done as follows:

1) Two approximate spot speeds are obtained: V_1 from the difference of passing times of the first axle over sensors 1 and 2 which gives a travel time over 1m and V_2 from the difference of passing times of the second axle over the same sensors which also gives a travel time over 1m.

2) Still using the same pair of sensors (1 and 2) four estimates of the value of the wheelbase can be obtained from the difference of passing times of the first and second axles over sensor 1 (T_1) and sensor 2 (T_2) multiplied by the spot speed (V_1 and V_2) previously calculated. As demonstrated by Seco (1991) a good estimate of the wheelbase value can be obtained by simply averaging the values V_1T_1 and V_2T_2.

Once the wheelbase has been determined the speed profile for each individual vehicle is achieved as a result of calculating the spot speeds on the other 14 single sensors by dividing the wheelbase by the difference of passing times of the first and second vehicle axle over each sensor.

4.10 Source of Errors

Before starting the data analysis it was necessary to check for errors resulting from the editing process. Three indicators were chosen to point out likely mistakes (a) the maximum speed, (b) the minimum speed at each data point, and (c) the total travel time in the link for each vehicle. A checking routine was established to search for errors by examining the coherence of those indicators.

High speed values have resulted from taking the passing time of the second wheel of the same axle as the passing time of the second axle (triple or quadruple passing time events have happened whenever the vehicle crossed over the tube at an angle). Low speed values were more unlikely to happen and suspicious values were checked and mostly reflect the behaviour of cautious drivers. Questionable travel time values would have represented an incorrect sequence of passing time events wrongly combining data from different vehicles.

In addition to the above, an inspection of individual speed profiles also enables the detection of errors since an acceleration and deceleration pattern were expected between each pair of calming measures.

4.11 Sample Size Requirements

The determination of a sample size depends on three factors:

a) the estimated sample standard deviation;

b) the desired confidence level; and

c) the precision required in the estimated mean speed.

Two distinct situations were considered to establish the required sample size firstly, for speed measurements to achieve speed along the link (speed profiles) and secondly, for spot speed checks downstream of a traffic calmed area.

With regard to spot speed measurements Kennedy et al (1973) recommend the measurement of at least 50, preferably 100 vehicles. According to Box and

Oppenlander (1976) the number of speeds to be measured is of the form:

$$N = \left(\frac{SK}{E}\right)^2$$

where: N = minimum sample size

S = estimated sample standard deviation

K = constant corresponding to the desired confidence level

E = permitted error in the speed estimate

According to the authors above, the error may range from ±5.0 to ±1.0 mph or even less and the standard deviations of spot speeds for an urban two-lane road equal to 4.8 mph. The constant corresponding to the 95% level of confidence is 1.96. Adopting the permitted error equal to 1.0 mph and applying these values to the formula above, gives a sample size of 88 observations.

However, spot speed measurements at Gale Lane before the implementation of traffic calming schemes (source: York City Council), indicated the sample standard deviation varying from 2.3 to 4.2 mph. Applying to that equation S = 4.2 and E = 1.0 for the 95% confidence level, resulted in a minimum sample size equal to 68 speed checks.

In the case of interest of some value other than the average speed, for instance 85th percentile, the appropriate formula to determine the required sample size is of the form:

$$N = \frac{S^2 K^2}{2E^2}\left(2 + U^2\right)$$

where: N = minimum sample size

S = estimated sample standard deviation

K = constant corresponding to the desired confidence level

E = permitted error in the speed estimate

U = constant corresponding to the desired speed statistic

Then, applying the same values as before to the formula above and using U = 1.04 (constant corresponding to the 85th percentile) gives a recommended sample size equal to 136.

Therefore, for the case of spot speed data collection using the radar gun a minimum sample of 68 vehicles was determined and in a similar way, 136 vehicles for the case of collecting data to build speed profiles.

4.11.1 Resulting Database

Concerning the data collection in order to achieve speed profiles, the completion of data processing for the six survey sites has resulted in a database of sample size shown in Table 4.9.

Table 4.9: Resulting database for each survey site

Sites	Database size		
	cars	vans	total
Livingstone Street	288	70	358
Foxwood Lane East	317	27	344
Foxwood Lane West	138	15	153
Gale Lane	286	26	312
Townend Street	210	30	240
Fourth Avenue	146	19	165

Due to the large samples of Livingstone Street and Foxwood Lane East, it was decided to divide them into halves in order to reserve one half of each for the validation process. The samples have been divided by separating odd from even observations which were ordered chronologically, thus resulting in two samples of equal size.

The study of spot speed downstream of a traffic calmed area is described in the following section and the actual number of observations concerning the spot speed survey is fully described in Appendix A.

4.12 Spot Speed Survey

The minor survey described here was carried out in order to assess whether drivers speed up after negotiating traffic calming devices in an attempt to recover the resultant time loss. This survey was designed to measure spot speeds at points further from traffic calmed links, so that, at such points, drivers would have recently experienced passing traffic calming measures.

4.12.1 Survey Methodology

This survey consisted of collecting spot speed data using a radar speed gun at three selected sites mentioned in the next section. Data collection was carried out in two stages, namely before and after the implementation of traffic calming schemes. In this regard, before and after spot speed studies could be accomplished.

Data was to be collected in accordance with the following criteria: on week days during off-peak hours, in daylight and in good weather conditions. Free flow cars and light goods vehicles would be the target population. Vehicle speed should be measured at points where there would be no calming measures and as little influence as possible of turning movements, traffic lights, and bus stops.

4.12.2 Site Selection

Some conditions had to be observed in the process of site selection to meet the survey requirements. The first condition was related to the implementation schedule of traffic calming schemes. Basically, the road was expected to be treated with calming measures in the near future to allow before and after spot speed studies.

The second condition was related to the fact that the calmed link should be part of a distributor road or should present some continuity to the network so that there must be a suitable point to monitor speeds.

Therefore, according to these conditions a suitable area was found in west York. The area comprises residential estates and is bounded by Gale Lane, Foxwood Lane and Askham Lane in a triangle shape (in Figure 4.2 the area is indicated by numbers 29 and 30). Three sites within this area were identified, Thanet Road, Front Street and Askham Lane.

4.12.3 Survey Stations

The survey stations were located in adjoining segments of Gale Lane (Thanet Road) and Askham Lane (Front Street) and they are schematically represented in Figure 4.17. Vehicles leaving the triangle area formed by Gale Lane, Foxwood Lane and Askham Lane were observed at the three stations. A brief description of each station is presented below.

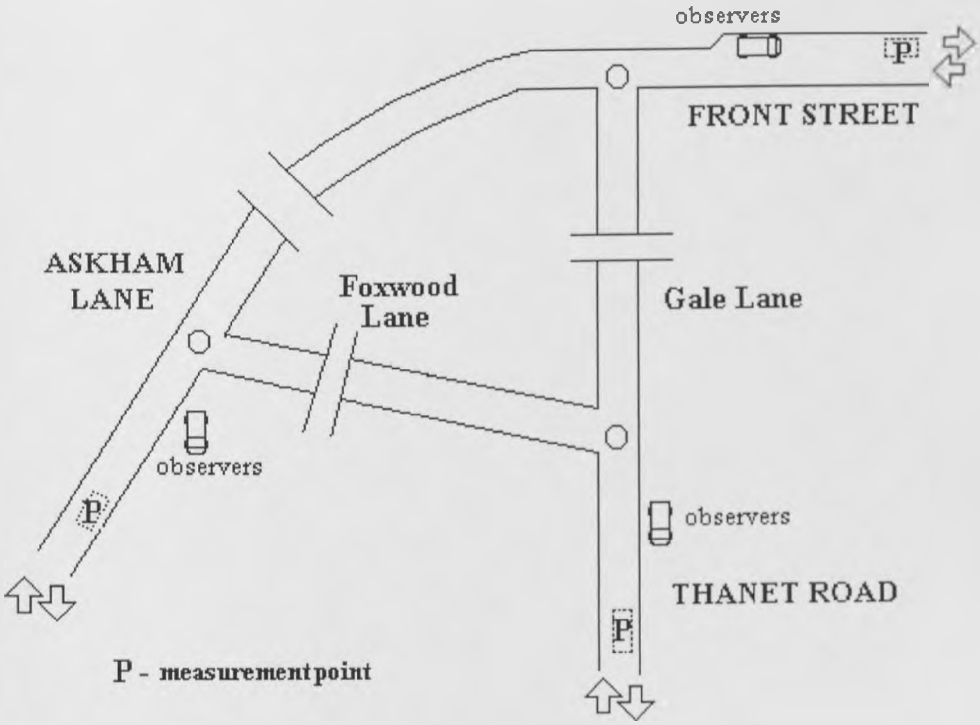


Figure 4.17: Spot Speed Survey Stations

Thanet Road Station

Thanet Road is a natural continuation of Gale Lane. There is a mini roundabout at the junction with Foxwood Lane and also a pelican crossing. The main restriction to free flow vehicles is related to the turning movements next to the station. Two turnings to the right are frequently used and likely to cause queuing traffic. The first one is the local access to the Bowls Club and the other busier one is an access to the Outer Ring Road avoiding the series of speed cushions in Foxwood Lane. A turning left to reach the Swimming Pool car park is not a main cause for traffic queues in the link but it sometimes contributes to worsen the problem.

Front Street Station

Front Street is a continuation of Askham Lane. There is a mini roundabout at the junction with Gale Lane. This junction leg presents a steep access due to gradient downhill from Askham Lane. Features in Front Street also restrict free flow vehicles. Although the traffic light is located further down from the station, sometimes it affects the survey because of long traffic queues from the stopline in addition to the effects of the bus stop near the traffic light. Queues and braking are also caused by the right turn off Front Street. Parked cars on the traffic lane are another traffic disturbance at the site.

Askham Lane Station

The station was located after the junction with Foxwood Lane towards the Outer Ring Road. Beyond the observation point the national speed limit applies. During the first stage of this survey Foxwood Lane was treated as a give-way at the junction. The greater traffic flow comes from Askham Lane and 95% of vehicles travelled in free flow conditions; no source of free flow restriction was identified. As part of the implementation of traffic calming schemes in Askham Lane a roundabout was constructed at the junction (March 94).

The changes on these three stations between before and after periods refer to:

a) traffic calming in Gale Lane;

b) traffic calming in Askham Lane with the construction of a roundabout at Askham Lane/Foxwood Lane; and

c) completion of the traffic calming scheme in Foxwood Lane from Bellhouse Way to the junction with Askham Lane.

4.12.4 Field Work

The definition of the stations and the point at which speed measurements were carried out reflected the following factors:

a) free flowing conditions and road geometry to avoid as much influence as possible on traffic conditions;

b) suitable place to operate the radar gun out of drivers' sight; and

c) distance greater than 80 m from the traffic calmed area. According to Homburger et al (1976) a passenger car on a level road achieves 40 mph at approximately 80 m from the start. Actually the survey stations were located more than 100 m from the end of a traffic calmed area. In addition to that the measurement point was downstream consequently increasing the overall distance.

Part of Foxwood Lane (from Gale Lane to Bellhouse Way) was traffic calmed in the first quarter of 1993. Therefore, at Thanet Road station a special strategy was applied during the before stage of the survey to classify two traffic streams (i) from Foxwood Lane and (ii) from Gale Lane ahead into Thanet Road. Hence, drivers who had experienced a traffic calmed link travelling on Foxwood Lane were identified.

The strategy consisted of two observation points. The first point was located near the junction (mini roundabout) and an observer recorded vehicles' registration plates and the direction they came from. At the second station there were two observers. One of them was reading the spot speed measured by the radar gun and the other one was recording speeds and registration plates. Matching the registration numbers enabled the identification of the origin of vehicles. However, this strategy could not be applied during all the survey days due to shortage of personnel. Then, only two observers had to undertake the task. While one observer was operating the speed radar gun the other one was recording the speed and observing the traffic flow at the junction. This solution was not the most convenient one but it resolved the shortage of observers. This solution demanded more integration between the observers and also more concentration.

At all three sites the two observers were inside a parked car and the radar gun was inconspicuous to road users. The surveys were conducted over one hour at each site (see Table 4.10).

Table 4.10: Spot speed survey timetable

		THANET Rd	FRONT St	ASKHAM Ln
	DAYS	**PERIOD**		
B	07/Jul/93	13:45 to 14:55	--	--
E	08/Jul/93	13:50 to 14:50	--	--
F	14/Oct/93	13:40 to 14:45	11:25 to 12:30	10:00 to 11:00
O	19/Oct/93	13:15 to 14:15	10:40 to 11:45	12:00 to 13:00
R	21/Oct/93	12:50 to 13:55	10:35 to 11:35	11:45 to 12:45
E	22/Oct/93	13:20 to 14:20	11:10 to 12:10	12:15 to 13:15
A F	25/Oct/94	12:15 to 13:15	10:05 to 11:05	11:10 to 12:10
T	26/Oct/94	12:05 to 13:05	10:00 to 10:55	11:00 to 12:00
E	27/Oct/94	12:05 to 13:00	10:00 to 10:55	11:00 to 12:00
R	02/Nov/94	12:15 to 13:10	10:05 to 11:05	11:10 to 12:10

4.13 Conclusion

The measurement of vehicle passing time at 16 predetermined points along traffic calmed links has been carried out successfully. Some operational problems concerning the equipment power supply, tubes replacement and the loss of signal from sensors caused disruption to data. However, the required data and sample size have been achieved in order to proceed with the data analysis described in the subsequent chapters. Downstream spot speed data has also been collected successfully. The data analysis is described in Appendix A.

CHAPTER 5

DATA PRESENTATION

This chapter is a data analysis starting point and presents the descriptive statistics calculated for the calibration sites Foxwood Lane West, Foxwood Lane East and Livingstone Street. Information on the distribution, variability and central tendencies of the recorded speeds are presented in this chapter. Descriptive statistics were generated by ASTUTE, a statistical analysis tool available in EXCEL for windows.

Speed profile and acceleration profile plots, for individual vehicles according to the entry speed in the link, are also presented as another tool to help viewing the data. Finally, this chapter presents hypotheses to be investigated in this work. They are related to the performance of measures and to drivers' behaviour and have been generated from this first examination of data.

5.1 Characteristics of the Sample

At first, the analysis of descriptive statistics was expected to be calculated for disaggregated data according to the type of vehicle - vans and cars and also for the whole data set. However, this idea could not be put into practice for Foxwood Lane East and Foxwood Lane West, since the number of surveyed vans is not sufficiently significant to be analysed individually. Apart from descriptive statistics, further analysis was based on cars plus vans combined.

The small sample of vans is a result of traffic flow composition verified at the survey sites, particularly Foxwood Lane West and Foxwood Lane East. The proportion of cars and vans in each database is similar to their proportion in the total traffic flow observed during the survey period, as demonstrated in Table 5.1, where the percentages in brackets correspond to the total traffic flow during the survey period.

Table 5.1: Sample size and proportion of cars and vans

SITES	CARS	VANS	TOTAL
FOXWOOD LANE EAST	155 90.1% [92.2%]	17 9.9% [7.8%]	172
FOXWOOD LANE WEST	138 90.2% [88.6%]	17 9.8% [11.4%]	153
LIVINGSTONE STREET	144 80.4% [82.7%]	35 19.6% [17.3%]	179

5.2 Descriptive Statistics

The completion of data processing for Foxwood Lane West, Foxwood Lane East and Livingstone Street has resulted in a database of sample size shown in Table 5.1 which takes into account the division of samples of Foxwood Lane West and Livingstone Street explained in the previous chapter. For each selected vehicle a speed profile containing 16 speed values along the survey link was achieved. This procedure was carried out for all survey sites.

5.2.1 Foxwood Lane West

The Foxwood Lane West survey link comprises a round topped hump at data point V5, a flat topped hump at data point V11 and a triple speed cushion at data point V16 (the letter V designates speed at a given data point). For simplification these measures will be termed throughout this study as hump (V5), table (V11) and cushion (V16). As this link is part of an extensive traffic calming scheme, a speed cushion plus a build-out precedes the hump and a triple speed cushion is downstream of the last measure in the survey link.

Figure 5.1 shows the average speeds obtained from the whole data set. It can be seen that the lowest speeds are recorded at the three measures. Of these, the table (V11) accounts for the smallest value and cushion (V16) for the highest value.

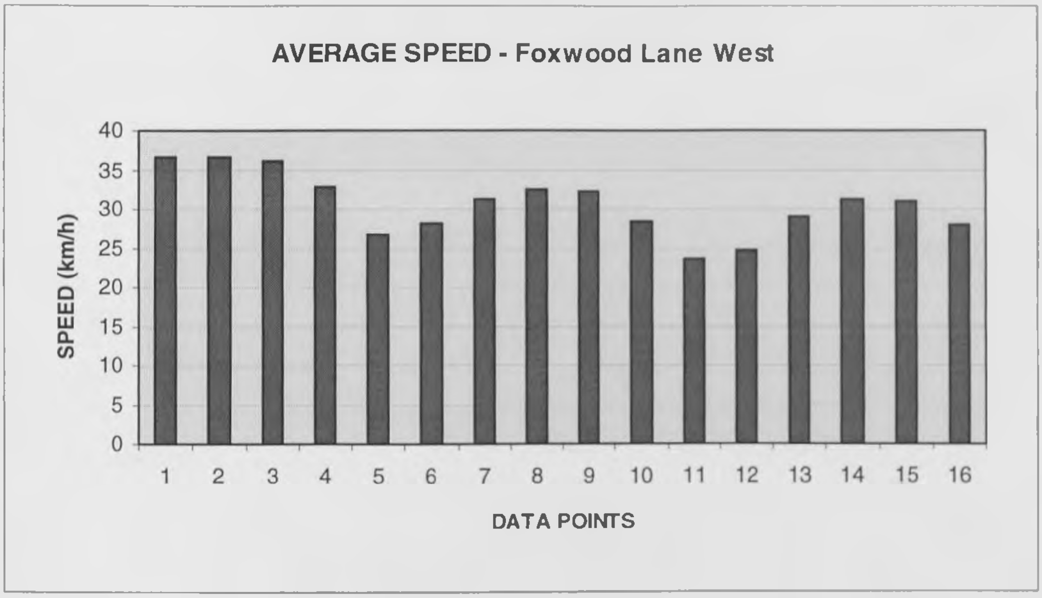


Figure 5.1: Average speed for Foxwood Lane West

A comparison of the median and the arithmetic mean for each survey point indicates the symmetry of the data distribution. As the two central tendency measures do not coincide, the positive values of skewness indicate that the data are clustered more to the left of the mean, with the most extreme values to the right. Those values in excess of 0.5 correspond to noticeable asymmetry (Metcalfe, 1994). The assumption of a normal distribution has been checked for data points V5, V11 and V14, which had high skewness and are of interest in the following chapter. Of these, the assumption is only rejected for V14 according to chi-square tests. Tables 5.2 and 5.3 represent those statistics obtained for all vehicles at Foxwood Lane West, the hatched areas indicate the position of the traffic calming measures.

In terms of the relative peakedness of the distribution, positive kurtosis values were observed at all data points except at V16, which indicate that the distribution is more peaked than would be true for a normal distribution whereas the negative value at V16 means that is flatter. V16 corresponds to the location of the speed cushion. The data points corresponding to the measures present high variance values, which indicate high dispersion of data about the mean. This is also verified for V1 and V2. Concerning these two data points, their trends at each of the three survey sites are very similar due to the small distance between them (1 metre).

Table 5.2: Statistics for all vehicles at each site: Foxwood Lane West

	Mean	Variance	SD	SE	Kurtosis	Skewness
V1	36.61	58.76	7.67	0.62	0.57	0.19
V2	36.57	58.04	7.62	0.62	0.57	0.18
V3	36.17	53.15	7.29	0.59	0.62	0.23
V4	32.85	43.25	6.58	0.53	0.47	0.41
V5	26.62	54.77	7.40	0.60	0.31	0.72
V6	28.27	42.27	6.50	0.53	0.87	0.82
V7	31.31	36.80	6.07	0.49	0.83	0.67
V8	32.53	37.27	6.11	0.49	0.61	0.55
V9	32.19	37.19	6.10	0.49	0.81	0.63
V10	28.49	34.47	5.87	0.47	1.43	0.89
V11	23.69	52.83	7.27	0.59	0.92	0.68
V12	24.67	40.75	6.38	0.52	2.31	1.15
V13	28.91	32.05	5.66	0.46	2.48	1.14
V14	31.36	33.49	5.79	0.47	1.90	0.88
V15	31.03	36.78	6.06	0.49	0.97	0.79
V16	27.90	61.81	7.86	0.64	-0.06	0.48

Table 5.3: Spread of the distribution for all vehicles at Foxwood Lane West

	Minimum	15th Percentile	Median	85th Percentile	Maximum
V1	15.12	29.12	36.00	45.57	62.80
V2	15.26	29.20	36.00	45.33	62.43
V3	15.08	29.04	35.43	43.88	61.35
V4	14.95	26.72	32.28	38.52	51.72
V5	13.40	18.62	25.71	34.00	50.39
V6	15.16	22.03	27.19	34.10	50.91
V7	17.58	25.96	30.49	36.08	51.72
V8	18.70	26.15	32.16	37.77	51.99
V9	18.49	26.23	31.74	37.71	52.83
V10	16.79	22.86	27.91	34.78	52.55
V11	9.28	16.44	23.05	30.64	51.99
V12	13.36	18.46	23.86	30.75	52.83
V13	17.66	23.95	27.99	34.43	53.69
V14	16.39	26.36	30.30	37.00	54.59
V15	16.16	25.64	30.16	37.55	52.55
V16	11.15	20.01	27.05	36.28	51.44

The data in Table 5.3 can be examined through the speed values in the 'box plots' shown in Figure 5.2. The upper and lower percentiles of the data (85th and 15th) are displayed at the top and bottom of the rectangles. The median is marked inside the rectangle. The length of lines from the ends of the rectangle indicates the largest observation (upper extremity: maximum) and the smallest observation (the lower extremity: minimum). The curve linking the minimum speed points is quite similar in shape to the median curve, revealing a more uniform driver behaviour in contrast to the upper limit curve which suggests a high speed driving style and a slight speed reduction at the first calming measure. This can be easily seen in speed profile plots shown in section 5.3.1 (Figure 5.12).

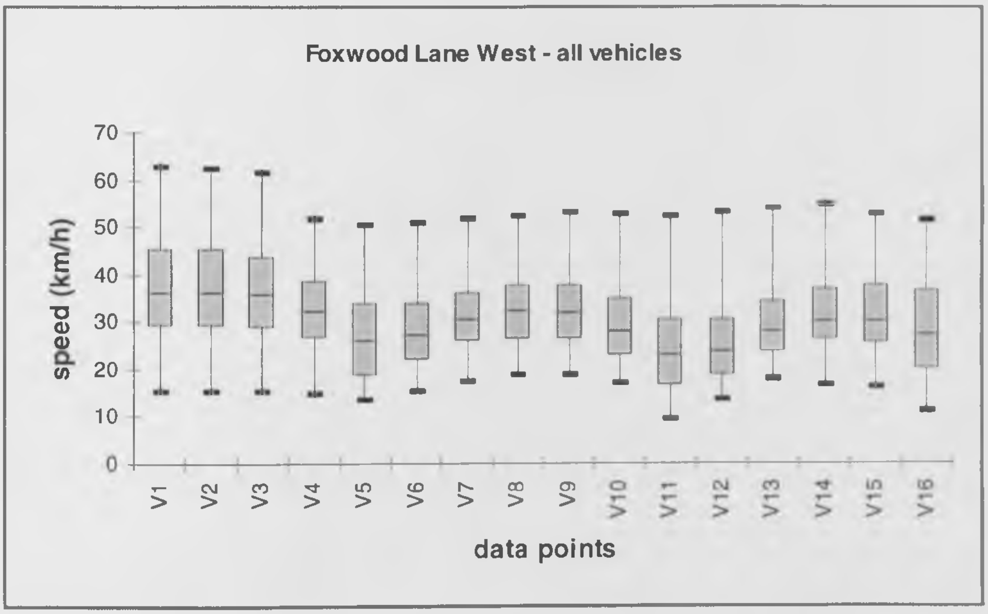


Figure 5.2: Maximum, 85th percentile, median, 15th percentile and minimum speed for Foxwood Lane West

Comparing the three different measures, hump (V5) accounts for the smallest speed range (the minimum subtracted from the maximum). Table (V11) presents the highest variability, however it shows the lowest 85th percentile speed whereas speed cushions present the highest 85th percentile speed of the three measures.

5.2.2 *Foxwood Lane East*

This stretch of road comprises three speed cushions at data points V4, V10 and V16. There is a triple cushion preceding the first cushion (V4) and also following the third cushion (V16).

Figure 5.3 shows the average speeds obtained at each data point for all vehicles. It can be seen that the lowest speeds are recorded at the measures (V4, V10 and V16) and these values are similar for the three cushions.

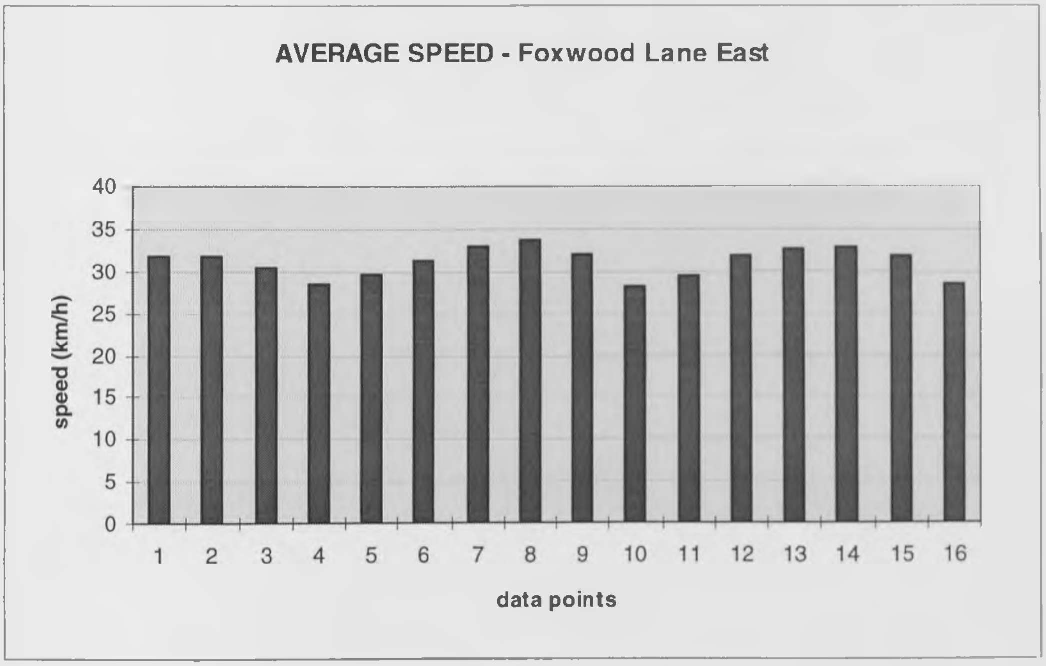


Figure 5.3: Average speed for Foxwood Lane East

Table 5.4: Statistics for all vehicles at each site: Foxwood Lane East

	Mean	Variance	SD	SE	Kurtosis	Skewness
V1	31.79	56.21	7.50	0.58	0.17	0.25
V2	31.76	54.83	7.41	0.57	0.12	0.26
V3	30.42	50.70	7.12	0.55	0.20	0.56
V4	28.52	62.36	7.90	0.61	-0.02	0.42
V5	29.63	48.82	6.99	0.54	0.10	0.54
V6	31.49	40.62	6.38	0.49	0.38	0.56
V7	33.16	37.87	6.16	0.47	0.40	0.45
V8	33.68	39.02	6.25	0.48	0.37	0.45
V9	32.07	41.69	6.46	0.50	0.34	0.65
V10	28.17	72.41	8.51	0.65	-0.32	0.32
V11	29.44	57.83	7.61	0.58	0.04	0.56
V12	31.96	44.91	6.71	0.52	0.39	0.57
V13	32.65	45.86	6.78	0.52	0.01	0.36
V14	32.86	43.88	6.63	0.51	-0.06	0.29
V15	31.80	42.86	6.55	0.50	-0.04	0.42
V16	28.52	65.79	8.12	0.62	-0.48	0.27

In the analysis of the distribution for all vehicles, the median and mean do not coincide at data points (as Table 5.4 and 5.5 illustrate) indicating that the distribution of data is not symmetrical. Positive values of skewness suggest that the data are clustered more to the left of the mean and a few data points show values of noticeable asymmetry. According to kurtosis values, the shape of the distribution is more peaked (lepto-kurtosis) apart from data points V4, V10, V14, V15 and V16.

Table 5.5: Spread of the distribution for all vehicles - Foxwood Lane East

	Minimum	15th percentile	Median	85th percentile	Maximum
V1	10.78	24.23	31.35	40.00	54.88
V2	11.43	24.26	31.27	40.00	54.24
V3	14.60	23.22	29.67	38.31	53.33
V4	11.72	20.06	27.71	37.22	52.44
V5	15.35	22.44	28.96	37.47	51.02
V6	16.62	24.80	30.60	38.57	52.44
V7	17.22	26.49	32.87	39.36	53.93
V8	17.60	27.02	33.37	40.14	54.88
V9	18.43	25.77	31.22	38.48	54.24
V10	9.95	19.08	28.04	37.35	51.86
V11	13.31	21.76	28.97	37.66	51.58
V12	13.79	25.50	31.35	38.96	51.98
V13	16.15	25.60	32.18	39.30	51.29
V14	16.05	25.68	32.37	39.31	51.29
V15	15.95	24.94	31.25	38.62	50.75
V16	10.92	20.07	28.12	36.71	50.49

It is worth mentioning that V4, V10, and V16 correspond to speed cushion locations and the same situation of lepto-kurtosis has been observed for the speed cushion in Foxwood Lane West, in the previous section. Those points also present a high dispersion of data about the mean as revealed through the variance. A high dispersion of data at all measures has also been verified at Foxwood Lane West.

Figure 5.4 represents the data in Table 5.5 in the format of 'box plots'. The 85th percentile curve shows the smallest variation in speed. The upper limit speed follows the profile pattern up to the second cushion; from this point on a uniform speed is found. The large size of the 'boxes' at the cushions (V4, V10 and V16) indicates the dispersion of data. The speed ranges at the cushions are similar and the variation among ranges is about 2.3 km/h. Median, 15th percentile and minimum speeds follow similar up and down trends which are more accentuated than the upper speed curves.

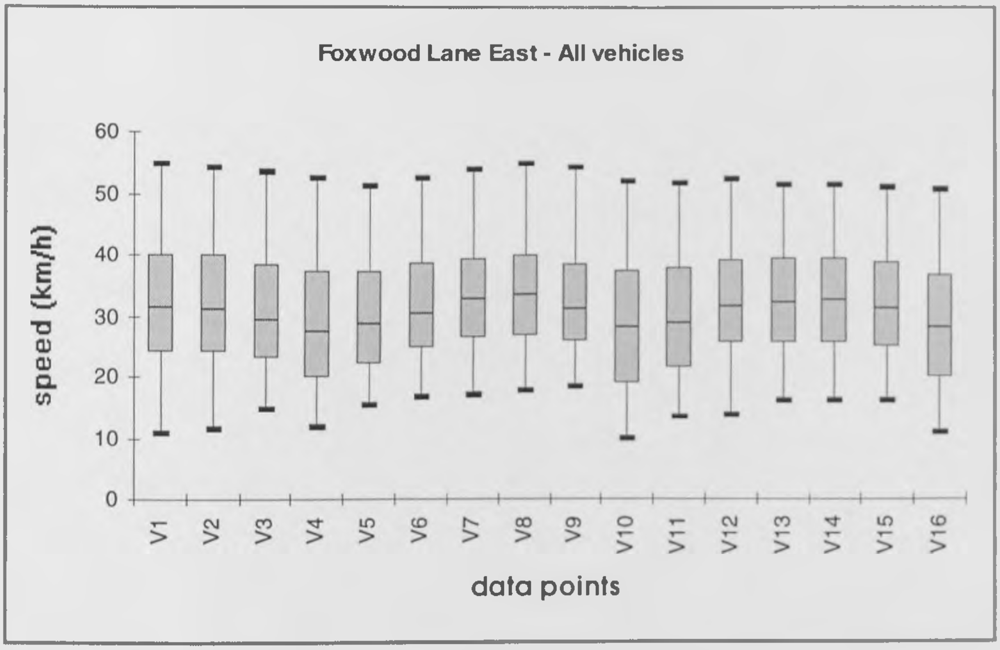


Figure 5.4: Maximum, 85th percentile, median, 15th percentile and minimum speed for Foxwood Lane East

5.2.3 Livingstone Street

Livingstone Street has two chicanes. The first one is located downstream of a T-junction. The midpoint of chicanes are respectively V6 and V14. There is a road junction where traffic must give way just downstream of V16 (approximately 25m).

Concerning average speed (Figure 5.5), the first chicane provokes more reduction in speed than the second one. Cars show higher average speed values at all data points. It is worth noting the trend of decreasing speeds after the last chicane (V14). This may be explained by the proximity to the give-way junction.

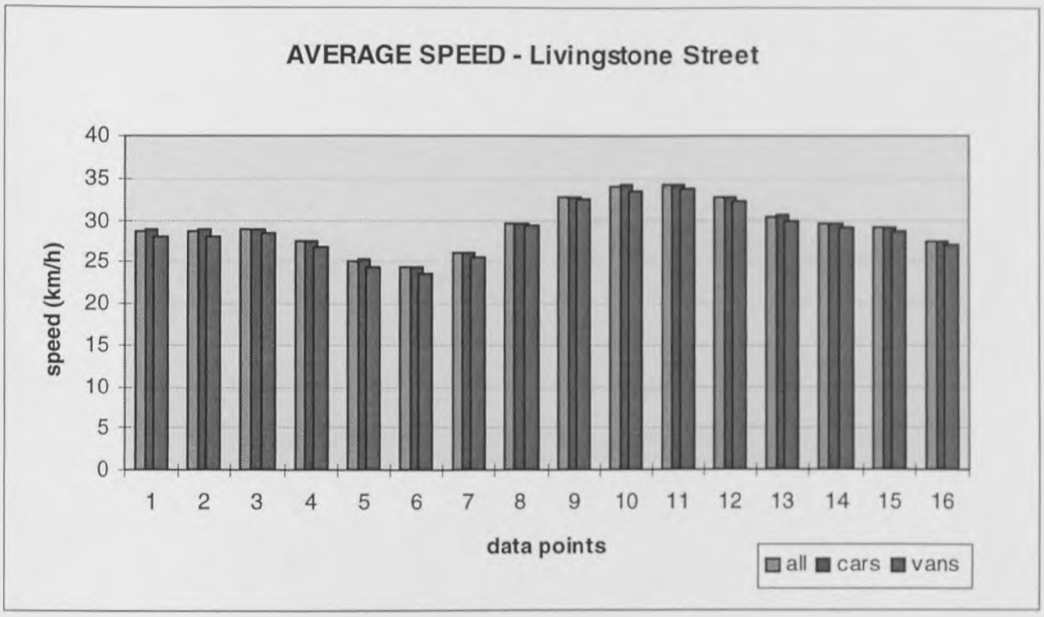


Figure 5.5: Average speed for Livingstone Street

The data in Tables 5.6 and 5.7, taking into account all vehicles, show slight differences between the median and the mean and suggest that the data distribution is not completely symmetrical. Data are clustered more to the left of the mean as the skewness indicates except for data points V1, V2 and V16 which cluster to the right, however skewness values do not correspond to noticeable asymmetry.

Table 5.6: Statistics for all vehicles at each site: Livingstone Street

	Mean	Variance	SD	SE	Kurtosis	Skewness
V1	28.75	24.82	4.99	0.38	0.05	-0.21
V2	28.79	24.58	4.96	0.38	0.01	-0.17
V3	28.88	20.85	4.57	0.35	0.32	0.08
V4	27.36	17.57	4.20	0.32	0.30	0.11
V5	25.16	18.74	4.33	0.33	0.37	0.11
V6	24.28	18.95	4.36	0.33	0.41	0.14
V7	25.92	18.48	4.30	0.33	0.26	0.26
V8	29.67	23.22	4.82	0.37	0.24	0.16
V9	32.75	27.56	5.25	0.40	0.29	0.10
V10	34.04	32.07	5.67	0.43	0.10	0.26
V11	34.12	33.49	5.79	0.44	-0.05	0.24
V12	32.67	34.32	5.86	0.44	0.11	0.36
V13	30.41	37.24	6.11	0.46	0.09	0.28
V14	29.62	37.59	6.14	0.46	-0.01	0.27
V15	29.10	27.58	5.26	0.40	-0.11	0.21
V16	27.44	19.91	4.47	0.34	-0.10	-0.02

Table 5.7: Spread of the distribution (all vehicles) Livingstone Street

	Minimum	15th Percentile	Median	85th Percentile	Maximum
V1	16.29	23.39	29.27	33.84	41.07
V2	16.22	23.22	29.44	33.99	41.23
V3	16.24	23.82	29.24	33.36	43.40
V4	16.74	22.81	27.60	31.50	41.16
V5	14.46	20.2	25.55	29.35	38.97
V6	12.52	19.97	24.45	28.84	36.74
V7	15.79	21.57	25.88	29.91	39.08
V8	17.41	24.82	30.15	34.12	42.99
V9	17.18	27.35	32.81	37.58	47.50
V10	19.93	27.86	33.84	39.33	50.28
V11	20.18	27.80	34.02	39.82	50.93
V12	20.53	26.42	32.48	38.64	50.68
V13	15.17	24.13	30.57	36.31	48.32
V14	15.12	23.01	29.79	35.69	47.23
V15	16.29	23.67	29.10	34.77	42.76
V16	14.05	22.44	27.57	31.99	40.12

The first chicane (V6) presents positive kurtosis whereas at the second one (V14) it is negative. They are also different in terms of the variance; V14 accounts for a high dispersion of data. This trend of high variance values is also observed in the stretch of road from V9 to V15 where the upper speeds are higher than those at the remainder of the data points.

The road design affects traffic differently as can be seen from the descriptive statistics. Speeds are higher before the second chicane than before the first chicane (Figure 5.6). This may be due to the longer length of road which enables drivers to attain such speeds. The lower speed at the first chicane may result from the shorter distance from the beginning of the road to the chicane in addition to the relatively low speed at the road entrance resulting from traffic turning at the T-junction.

In terms of data variability, the second chicane (V14) presents similar speed values and a similarly very wide range to the previous data point (the distance between V13 and V14 equals to 6.2 m).

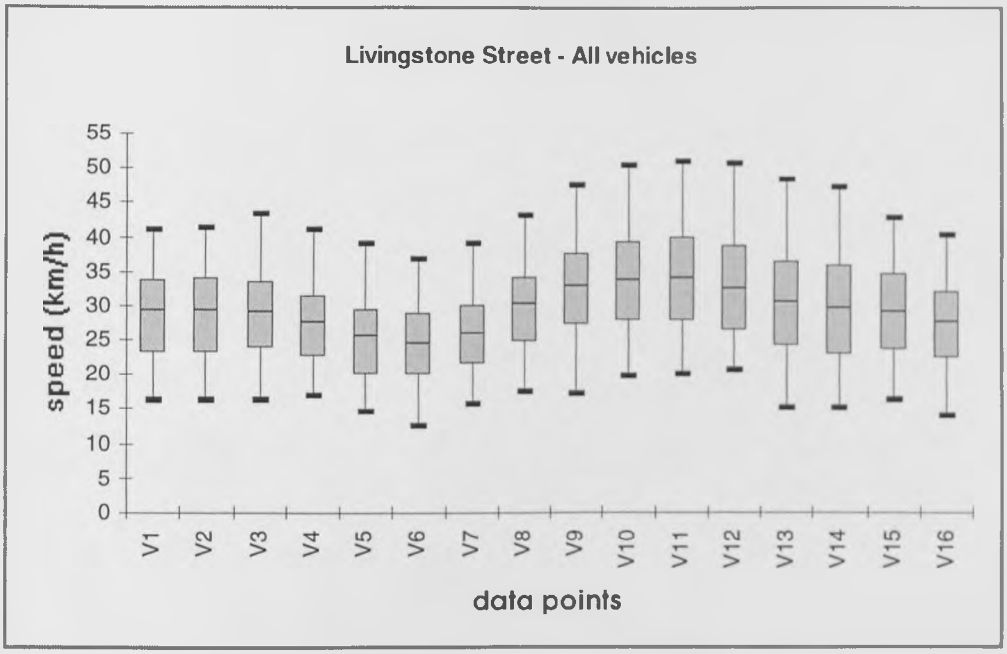


Figure 5.6: Maximum, 85th percentile, median, 15th percentile and minimum speed of all vehicles in Livingstone Street

Box plots have also been presented according to vehicle categories: cars and vans (Figures 5.7 and 5.8, respectively). A first examination of these plots reveals that the upper speed limits in Figure 5.6 (representing all vehicles) correspond to the cars' upper limits in Figure 5.7.

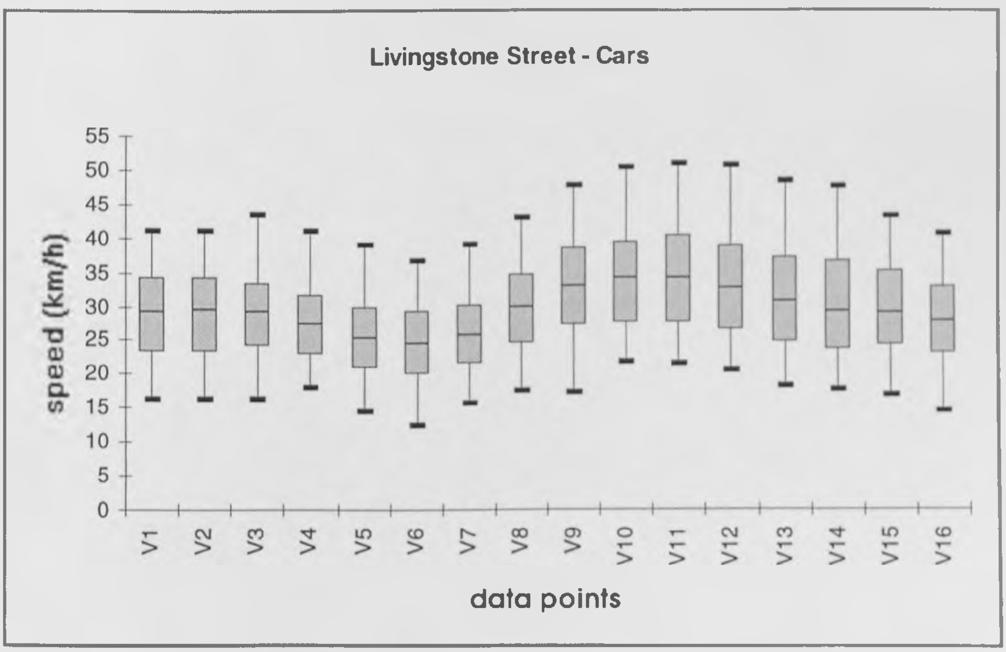


Figure 5.7: Maximum, 85th percentile, median, 15th percentile and minimum speed of cars in Livingstone Street

With regard to the lower speed limit, this also represents speeds recorded for cars apart from V4, V10, V13 and V14. Similar shapes of speed curves (maximum, 85th and 15th percentile and median speeds) are observed for both categories.

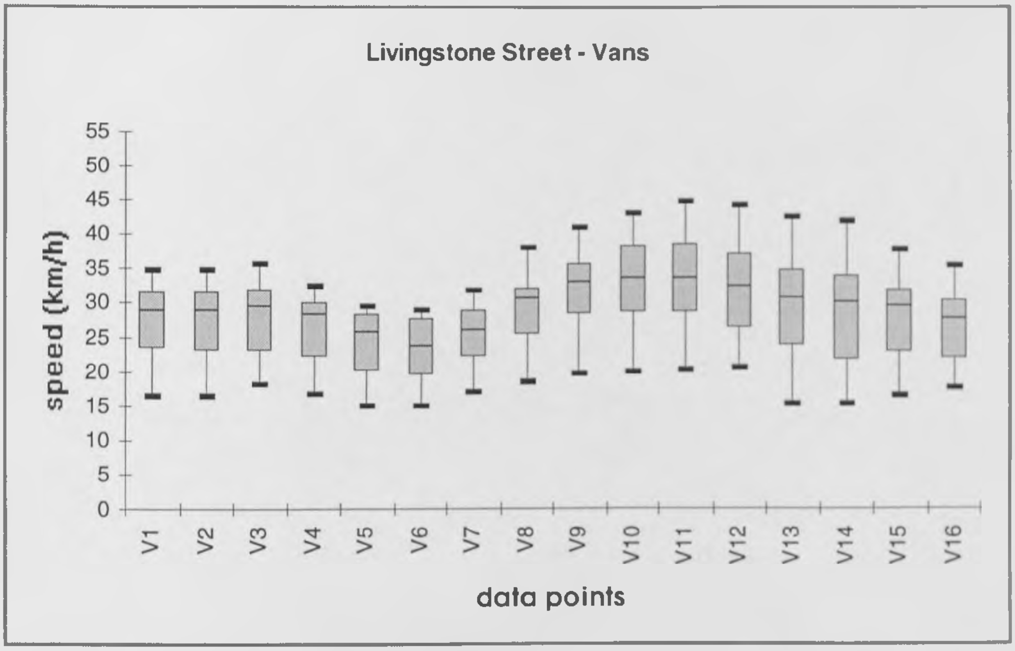


Figure 5.8: Maximum, 85th percentile, median, 15th percentile and minimum speed of vans in Livingstone Street

Vans and cars have also been analysed through the input speed distribution (V1) and Figure 5.9 presents a histogram of the input speed by type of vehicle.

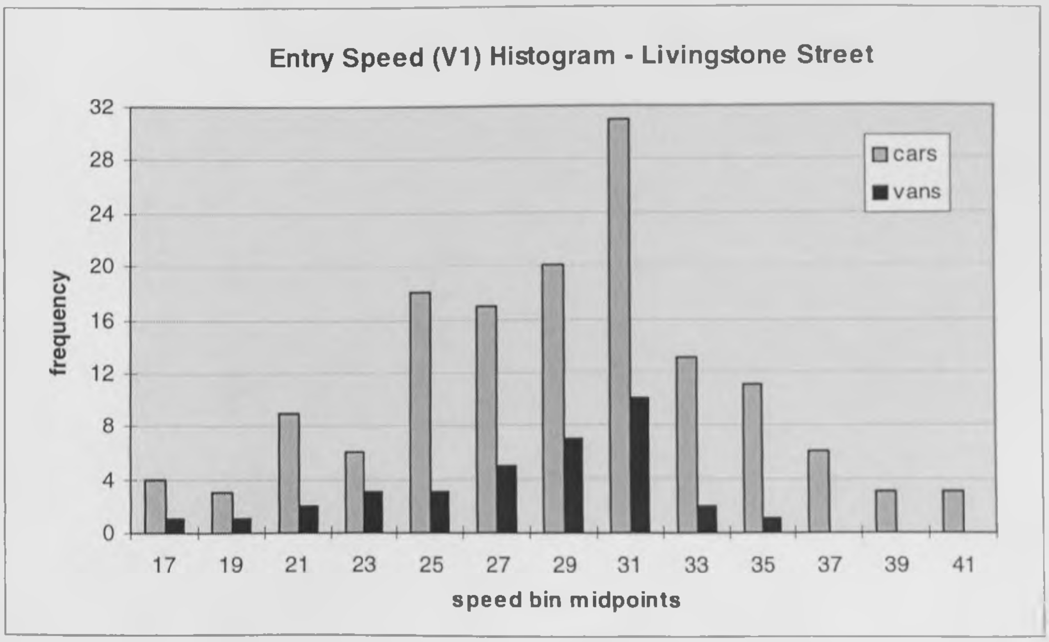


Figure 5.9: Histogram for vans and cars according to the entry speed (V1)

The sample of vans is concentrated in the mid range speeds and the distribution is clustered to the left whereas cars present a more uniform distribution which reaches the high speed bins.

5.2.4 Discussion

The descriptive statistics calculated by data points and presented for each site has provided some important information about the data collected. The normal distribution is commonly used to describe the distribution of vehicle speeds (Taylor and Young, 1988). The measures of the spread of the distribution confirm that the data can be considered normally distributed apart from a few data points of Foxwood Lane West. Therefore, parametric tests can be applied to analyse the remaining data.

The traffic calming measures appear to reduce the speed variability, especially the 85th percentile values, as the box plots have shown. The second chicane in Livingstone Street does not follow that trend, and the 85th percentile speed at this measure is greater than at many other data points. This is almost certainly due to the effect of the downstream junction.

The examination of the effect of the different types of measures on median and average speeds at the measures points out differences in impacts by type of measure. Table 5.8 provides a summary of mean and median speed values at measures and between measures for the three sites. The sites under consideration present four different types of measures, namely hump, table, chicane and speed cushion.

Foxwood Lane West accounts for three out of the four types (hump, table and cushion). The table (V11) accounts for the smallest average speed and the cushion (V16) for the highest one. Considering the three speed cushions in Foxwood Lane East, average speeds recorded at the measures are very similar indicating similar impact by type of measure. Average speed between cushions (V8 and V14) present slightly different values. In terms of average speed, the cushion in Foxwood Lane West results in lower speeds than any of the three cushions in Foxwood Lane East.

Table 5.8: Summary of mean and median speeds at the measures and between measures for all sites

SITES	Speed at the measure (km/h)		Speed between measures (km/h)	
MEASURES	mean	median	mean	median
Livingstone Street:				
Chicane V6	24.28	24.45		
V11			34.12	34.02
Chicane V14	29.62	29.79		
Foxwood Lane East:				
Cushion V4	28.52	27.71		
V8			33.68	33.37
Cushion V10	28.17	28.04		
V14			32.86	32.37
Cushion V16	28.52	28.12		
Foxwood Lane West:				
Hump V5	26.62	25.71		
V8			32.53	32.16
Table V11	23.69	23.05		
V14			31.36	30.30
Cushion V16	27.90	27.05		

Chicanes in Livingstone Street show different average speeds at the devices. Average speed at the second chicane (V14) is 5 km/h greater than at the first chicane (V6). Moreover, comparing the measures at the three sites, the highest average speed at the measure is found at the second chicane in Livingstone Street. The highest average speed between measures is also found at this site, between the two chicanes (V11).

Median speeds at all sites follow the same trends as average speeds. Median speed values are generally smaller than the average ones. Of these, Livingstone Street measures present the more negligible differences. Nevertheless, the largest differences encountered do not exceed 1 km/h, for instance V14 and V5 (Foxwood Lane West), V4 and V16 (Foxwood Lane East).

There is not a clear relationship between the speed between measures and the speed at the upstream measure, since the highest speed between measures (V11 Livingstone Street) follows one of the lowest speeds at a measure. This may suggest that speed between measures depends on another variable, for instance the distance to the downstream measure in addition to the crossing speed at the measure, which may reflect the type of measure.

5.3 Speed Profile Overview

So far, data presentation has focused on the analysis of data grouped by data points along the survey links and the variable distance between them has not been taken into account. In this section speed data will be presented as a function of the actual distance between data points. This relationship between speed and distance has been termed a speed profile. Speed profiles of individual vehicles have been plotted for each site according to entry speed bins. In order to facilitate the interpretation of speed profile plots, Table 5.9 presents the cumulative distances in respect of each data point for each survey site. The actual positions of measures are highlighted in this Table.

Table 5.9: Cumulative distances (in metres)

Data Points	**Foxwood Ln West** distance (m)	**Foxwood Ln East** distance (m)	**Livingstone St** distance (m)
1	0	0	0
2	1	1	1
3	8	12	12
4	22	22	22
5	36	32	32
6	46	42	39.2
7	58	56	48.9
8	70	66	58.9
9	79	89.8	71.9
10	94	105	83.9
11	103	115	90.9
12	112.4	130	108.9
13	122.4	145	122.9
14	132.4	155	129.1
15	145.4	170	144.1
16	159.4	185	154.1

5.3.1 Foxwood Lane West

In order to help viewing the sample speed distribution in terms of the entry speed in the link (V1), a speed frequency diagram dividing the data into class intervals equal to 3 km/h is presented in Figure 5.10. Therefore, speed measured at data point 1 is the variable used in the histogram. The shape of the distribution reveals that data are more clustered to the left of the mean with the extreme values to the right, as was mentioned previously from the examination of skewness values.

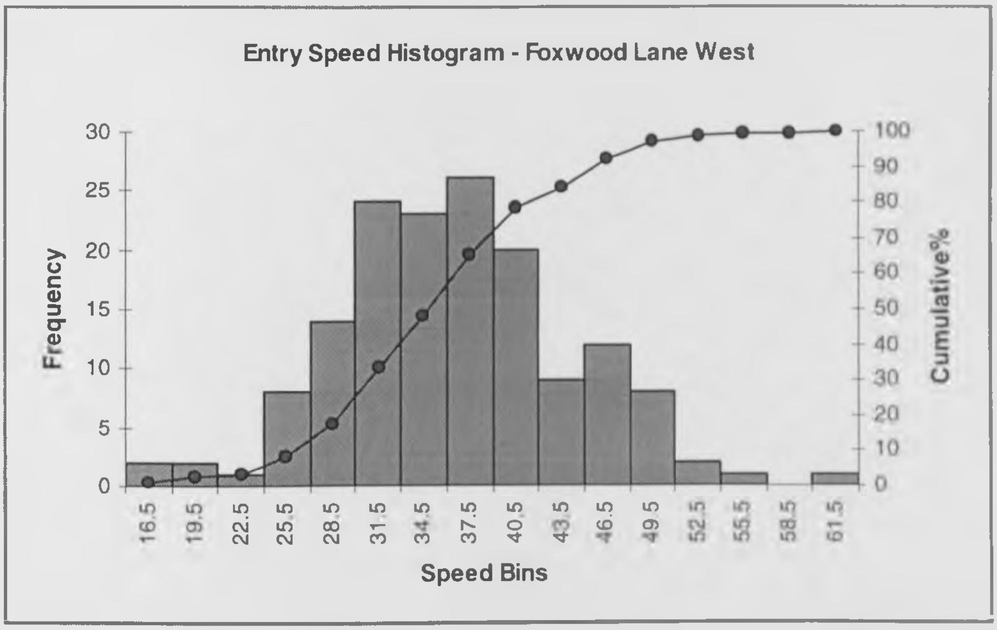


Figure 5.10: Entry speed histogram - Foxwood Lane West

In order to reduce the number of plots and also to keep a balance in the number of speed profiles presented in the same figure, low frequency classes have been combined together; therefore, six speed profile figures will be presented for Foxwood Lane West.

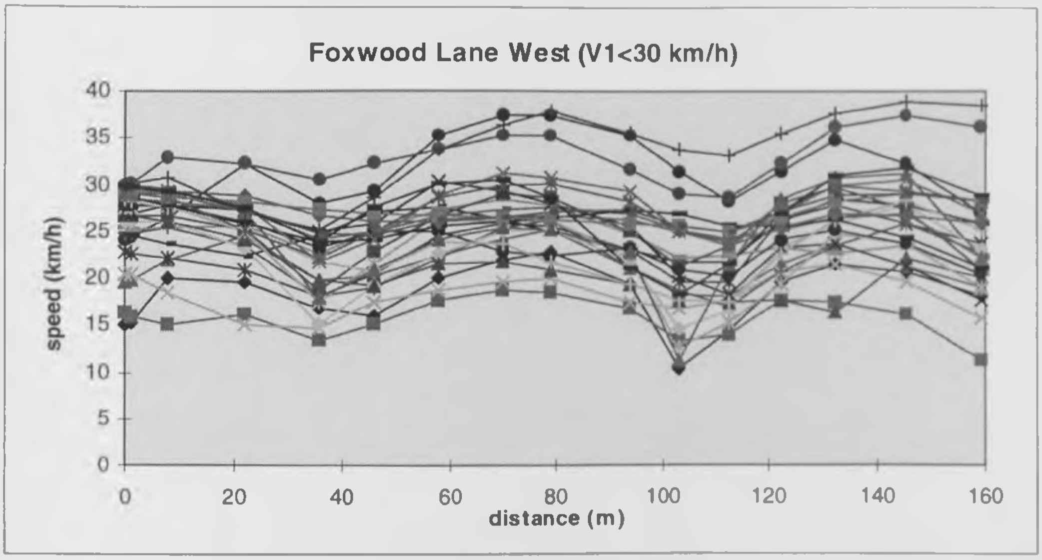
Figures 5.11 and 5.12 plot the speed profiles for each vehicle in each of these groups. It can be observed from these speed profile plots that the input speed (entry speed) is either the highest speed along the survey link or, if not, maximum speeds are maintained within small variations.

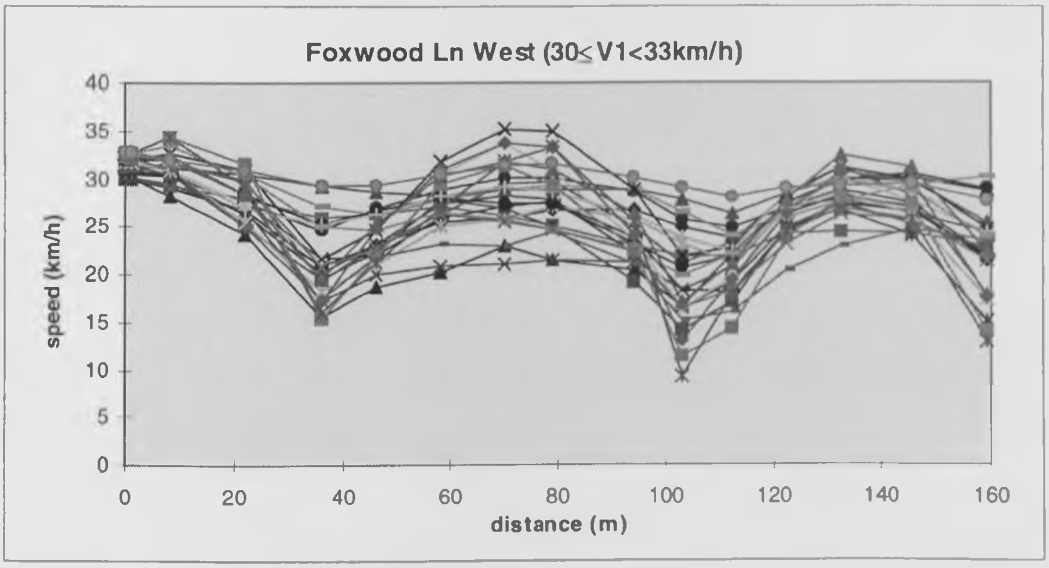
With regard to the trends of speeds at the measures, the hump (V5 at 36 m from the origin) shows the smallest speed variability, that is speeds are concentrated on small intervals. The table (V11) presents the lowest speeds and a high variability. The cushion (V16, the last data point in the link) accounts for a great speed variability and the highest speeds among measures. Higher speeds are particularly found for vehicles entering the link at speeds between 33 and 40 km/h.

Speed change rates are another factor that can be observed in those plots through the slope of the lines linking data points. The slopes represent the acceleration or deceleration between two data points. The comparison of the slope of the lines preceding the calming measures indicates the deceleration rate to negotiate a measure.

Steeper slopes precede the hump and the table whereas the gentlest slopes are found before the cushion. With regard to the cushion, in some cases the speed profile plots reveal drivers speeding up instead of slowing down to negotiate the last measure.

The examination of individual speed profiles demonstrates that the higher the entry speed the smaller the speed reduction and therefore, the smoother the speed profiles. Unusual driver behaviour appears more frequent within the highest speed ranges and at high speeds. Calming measures seem to achieve only slight speed reductions for these drivers; for instance one driver negotiates all measures at a constant high speed of about 52 km/h. In contrast, low entry speeds (less than 30 km/h) present more uniform speed profiles evenly spread along the speed axis (*y*) throughout all data points in accordance to the entry speed, therefore revealing a more uniform behaviour. This speed bin includes the greatest proportion of the lowest speeds observed along the link.





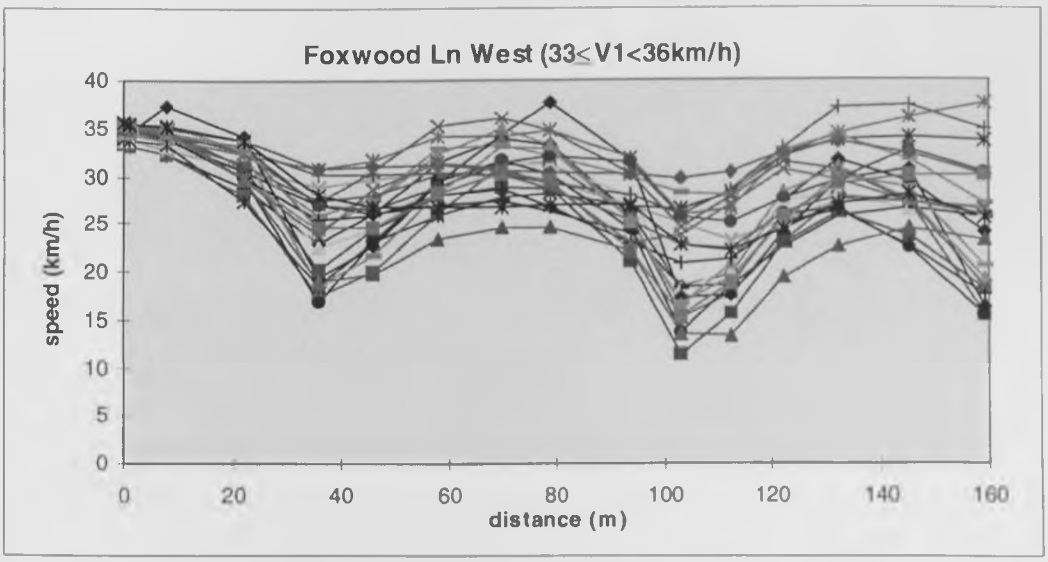
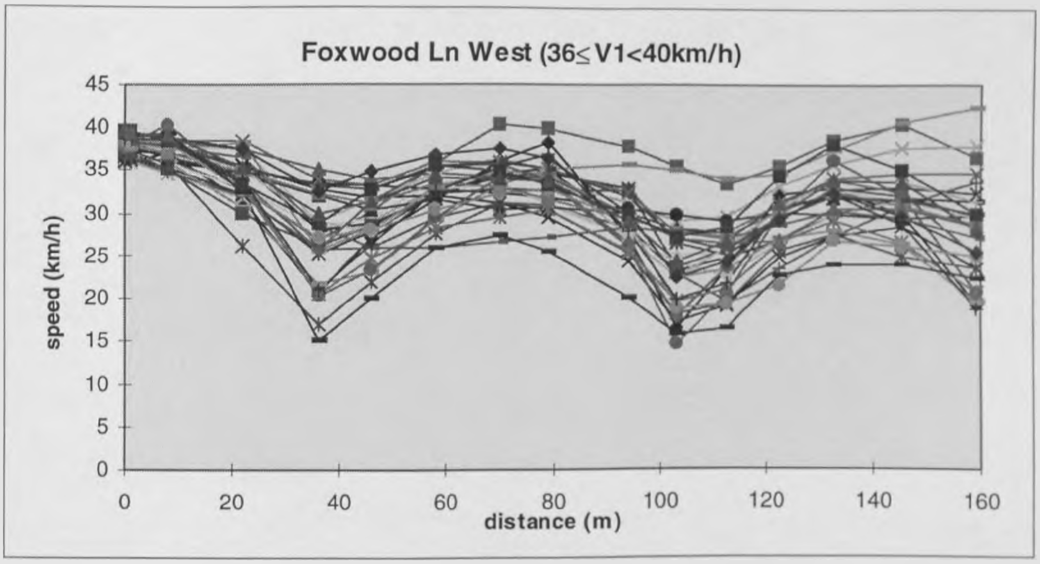
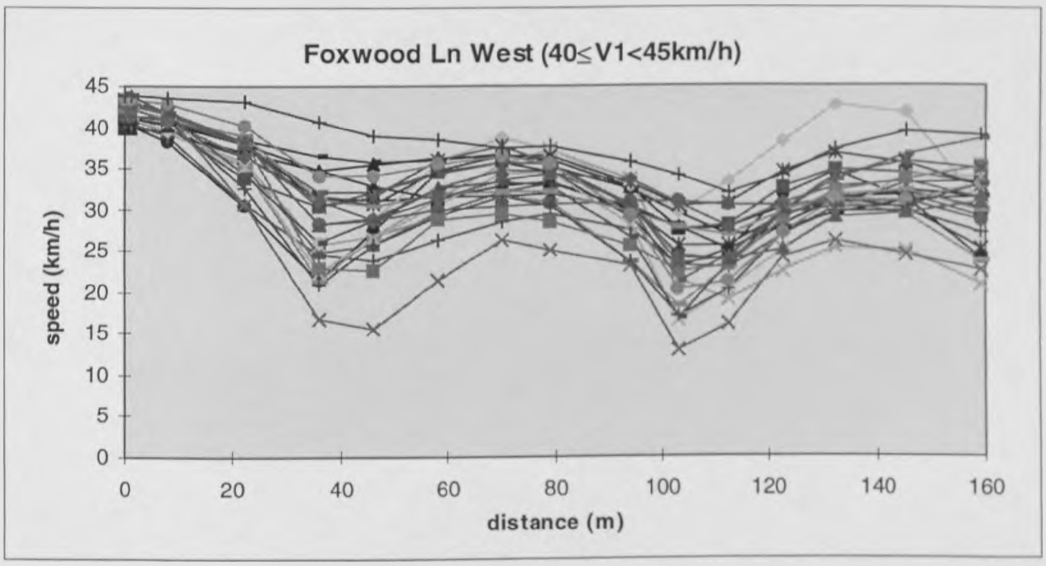


Figure 5.11: Speed profile plots for Foxwood Lane West (V1<36 km/h)





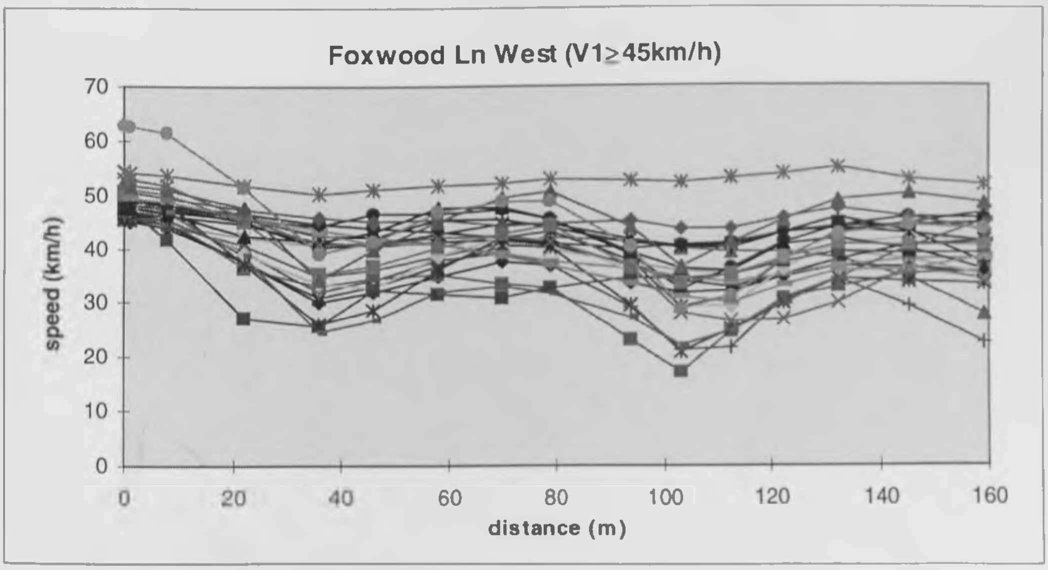


Figure 5.12: Speed profile plots for Foxwood Lane West (V1≥ 36 km/h)

5.3.2 Foxwood Lane East

A speed frequency diagram for the first data point (V1) has been plotted for Foxwood Lane East data using 2 km/h class intervals (Figure 5.13).

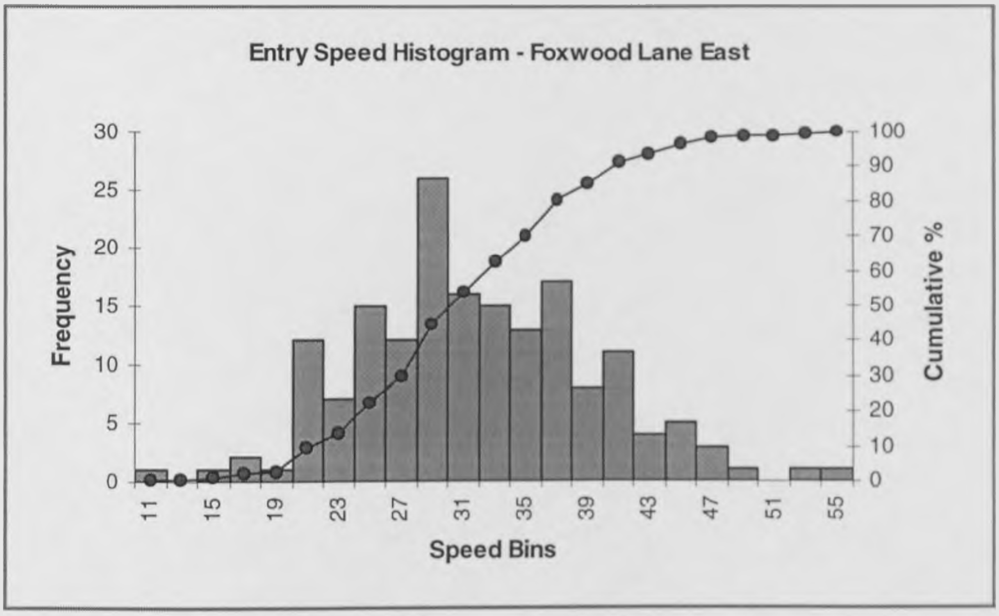


Figure 5.13: Entry speed histogram - Foxwood Lane East

In general, speed profile plots for Foxwood Lane East are remarkably different from those of Foxwood Lane West with regard to the entry speed. The latter presents entry speed values usually closer to the maximum speed found between the calming measures. Entry speed values in Foxwood Lane East are closer to the speed at the first cushion (V4). The median entry speeds were 34.5 km/h for Foxwood Lane West and 31.0 km/h for Foxwood Lane East.

This situation in Foxwood Lane East may result from the position of the first sensor on the road. Usually, the area between measures from midway up to around 60% of the spacing between measures in the direction of travel is the point at which maximum speeds are attained. The location of the first sensor in relation to the calming measure that precedes the first measure considered in the surveyed link was greater than 60% of the overall distance, consequently corresponding to a point where vehicles have already started the deceleration manoeuvre to negotiate the calming measure.

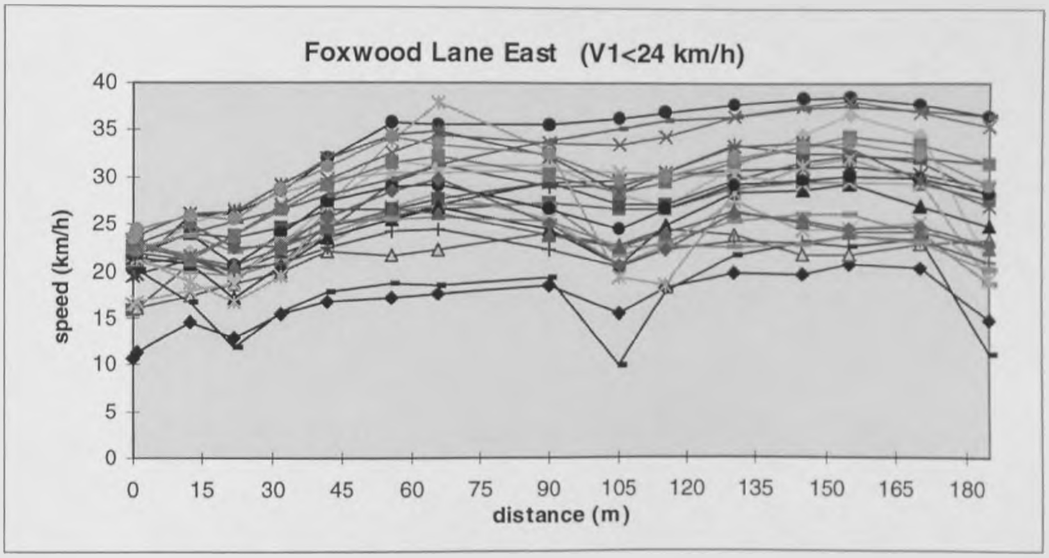
Furthermore, the existence of a junction may also result in lower entry speeds for vehicles turning into Foxwood Lane East from that junction.

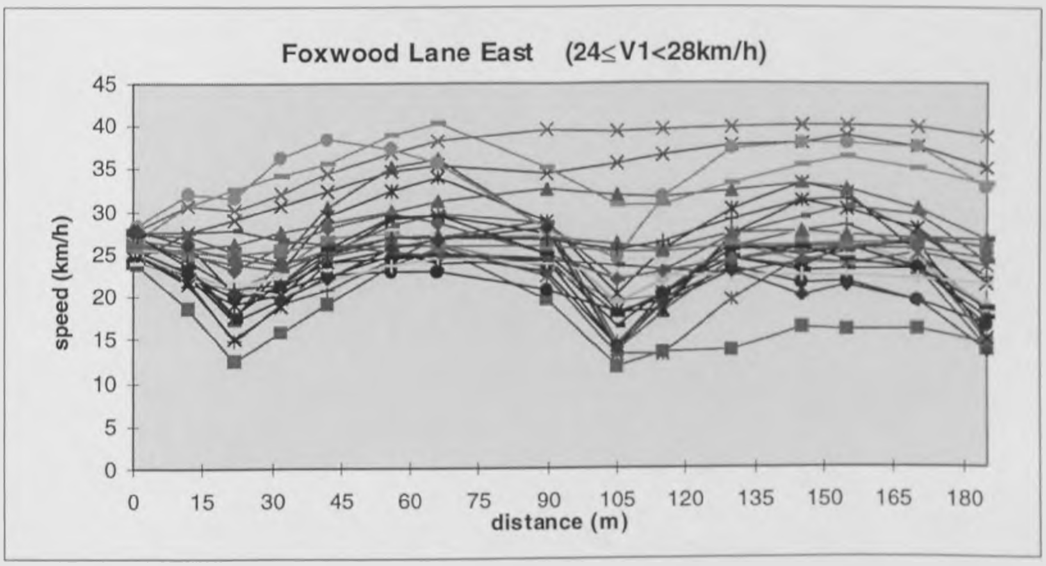
Individual speed profile plots have been grouped into entry speed classes (mostly 4 km/h intervals) and are presented in Figures 5.14, 5.15 and 5.16. In these figures the corresponding position of cushions in relation to the origin (V1) in metres is: V4 at 22 m, V10 at 105 m and V16 at 185 m (the end of the link). Similar speed variability is observed at the second and third cushion (V10, V16) whereas the first cushion mainly shows a small variability in the recorded speeds. The dispersion (spectrum of lines) of speed profile plots is observed at all entry speed bins and the dispersion increases from the first cushion onwards.

Some general trends can be extracted from the examination of speed profiles. Maximum speeds between measures are frequently higher than V1. There are a great proportion of drivers travelling at near constant speed after the midpoint between the first and second cushion (about 50 m from the origin) which suggests that those drivers tend to ignore traffic calming devices.

Speed profile curves are more variable for lower speeds (at the measure) indicating a great change in speed to negotiate the measures. The relationship between the speed profile curves and entry speeds also indicates the higher the entry speed the more the speed profile curve resembles a straight line; entry speed plots for V1 $\geq$ 42 km/h illustrate this. Consequently, the slopes that indicate acceleration and deceleration are steeper for lower speeds at the measures and more gentle for higher speeds especially in manoeuvres which involve small speed changes.

This particular combination of traffic calming measures appears less aggressive and constraining and it enables drivers to cross the link at a relative high speed (greater than 40 km/h) for a calmed area.





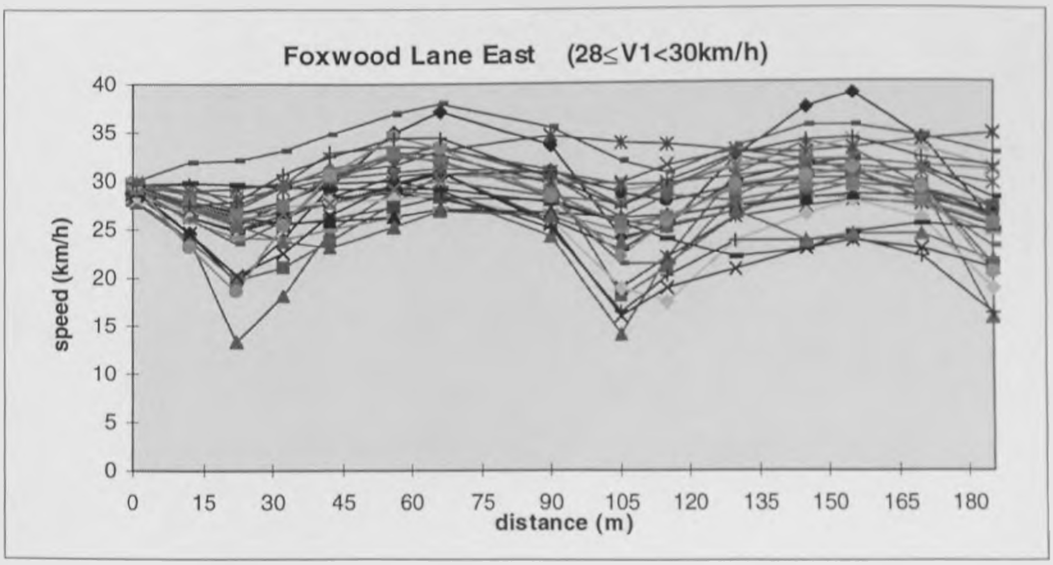


Figure 5.14: Speed profile plots for Foxwood Lane East (V1<30 km/h)

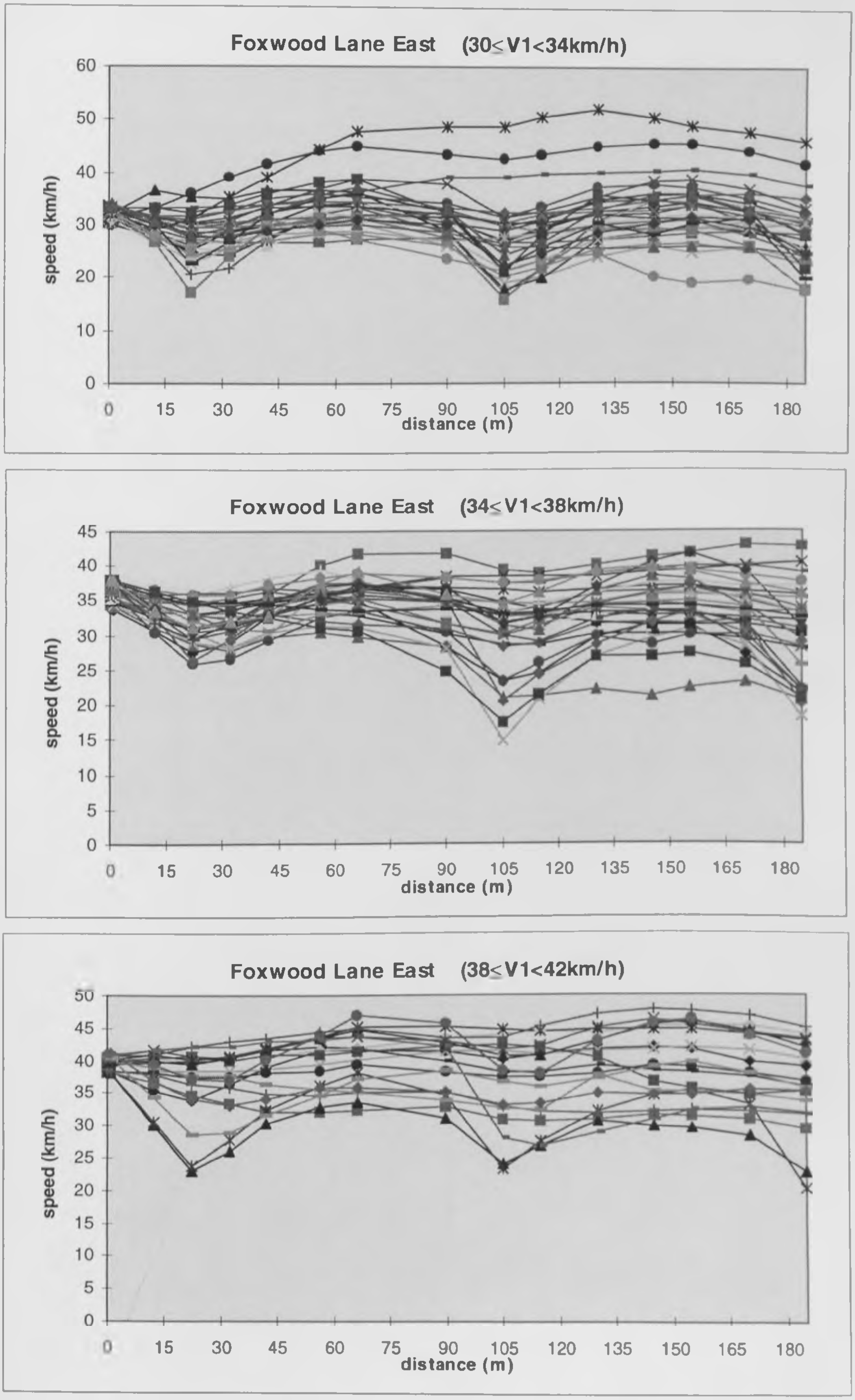


Figure 5.15: Speed profile plots for Foxwood Lane East (30≤ V1<42km/h)

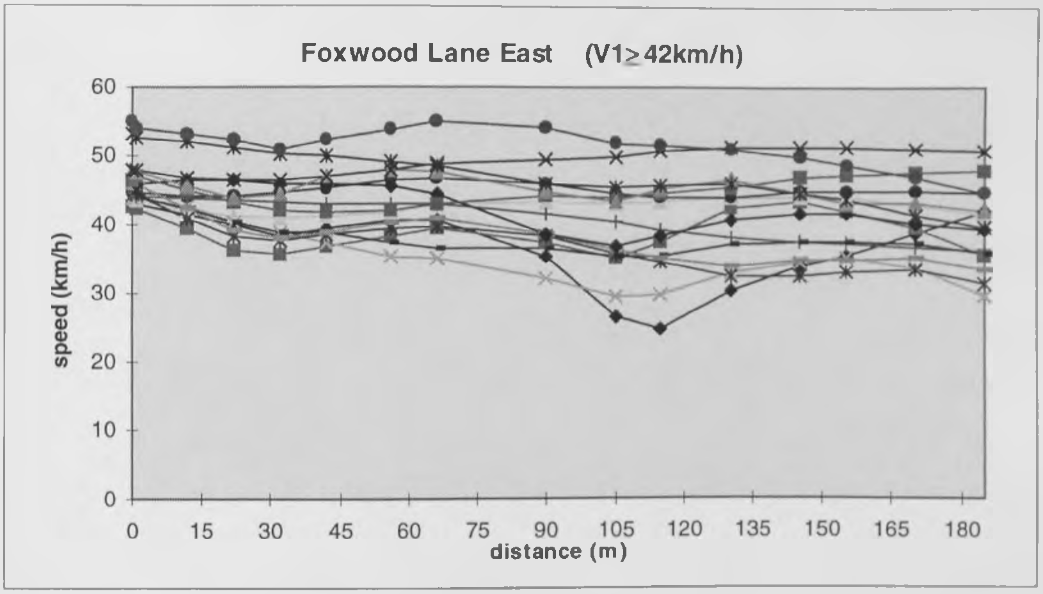


Figure 5.16: Speed profile plots for Foxwood Lane East (V1≥42 km/h)

5.3.3 Livingstone Street

The entry speed histogram built taking into account the first data point (V1) indicates that the majority of vehicles enter the link at speeds less than 33 km/h (Figure 5.17).

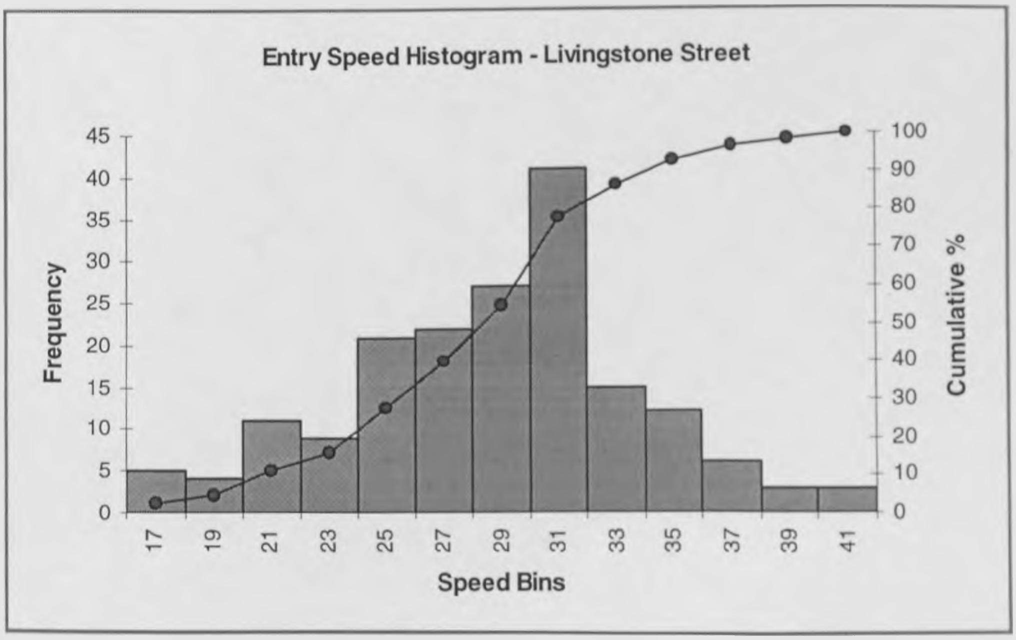


Figure 5.17: Entry speed histogram - Livingstone Street

Speed profile plots (Figures 5.18, 5.19 and 5.20) have been grouped by class intervals varying from 1 to 4 km/h to facilitate their comprehension. The position of the chicanes in relation to the origin is: V6 at 39.2 m and V14 at 129.1 m. In terms of the speed variability at the chicanes, V14 presents a clear high dispersion of speeds and also the highest speed values, however the differences between minimum speeds at the chicanes are not so distinct.

In general, speed profile plots show that the data point which accounts for the maximum speed before the first chicane coincides with V1 (first data point), but some vehicles show the maximum speed being attained at V3 (12 m from the origin) as an indication that the deceleration manoeuvre starts at V3. This behaviour is often found for entry speeds < 30 km/h.

Speed profile plots for Livingstone Street follow a general trend of two distinct curves in that the second curve has a large curvature. The slopes in the vicinities of the first chicane are steeper than those verified for the second chicane. Slopes after the second chicane still indicate speed reduction as mentioned in an earlier section. However, an acceleration phase can be observed after the second chicane for a few vehicles in all speed profile plots. Unusual behaviour seldom occurs and constant high speed does not occur at all.

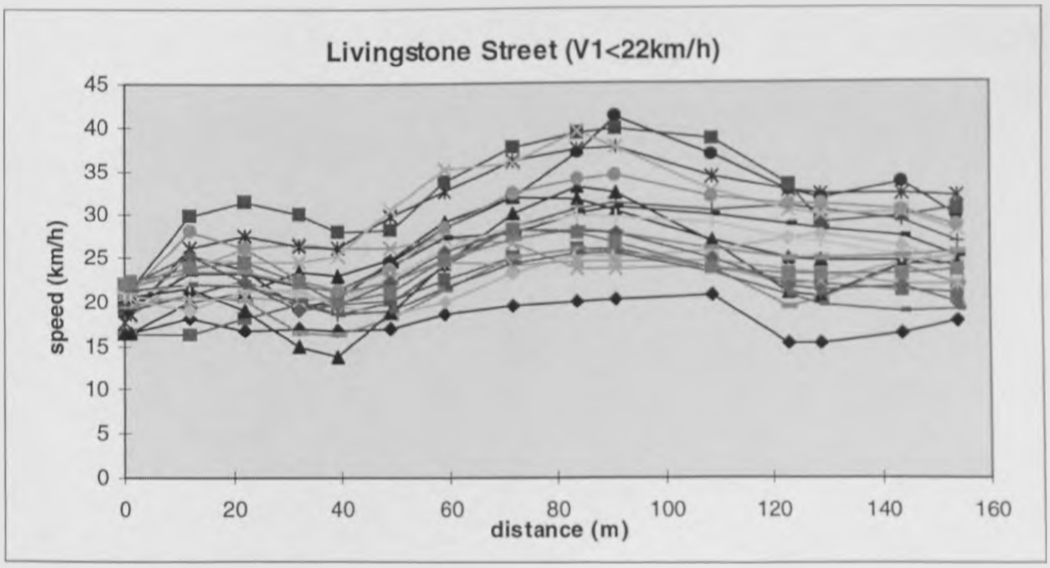


Figure 5.18: Speed profile plots for Livingstone Street (V1< 22 km/h)

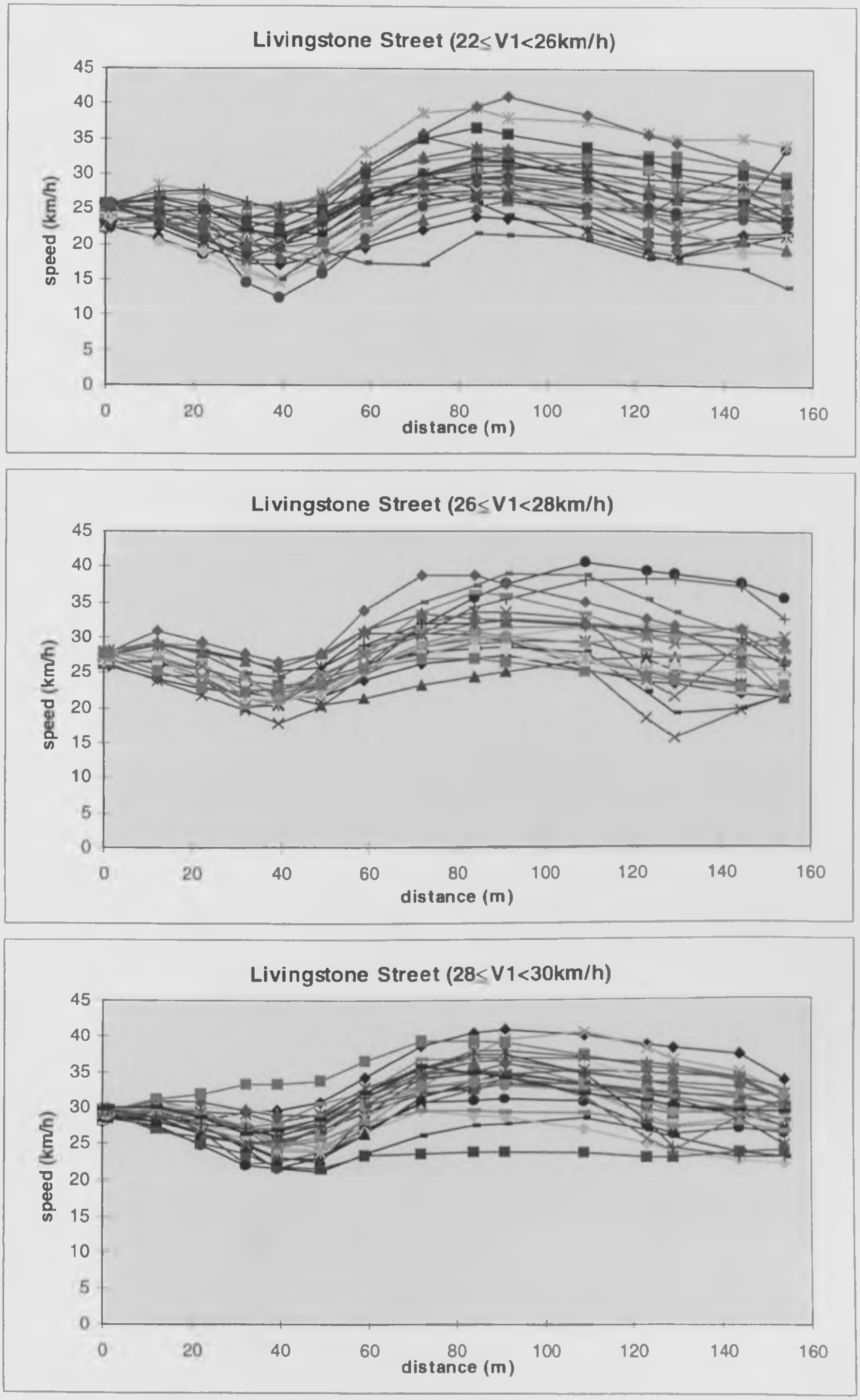
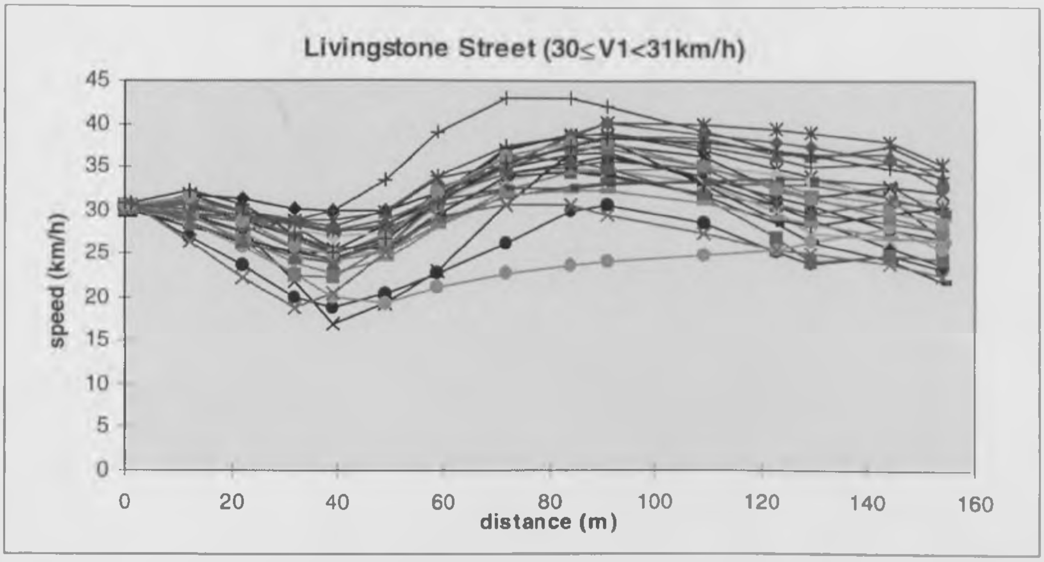
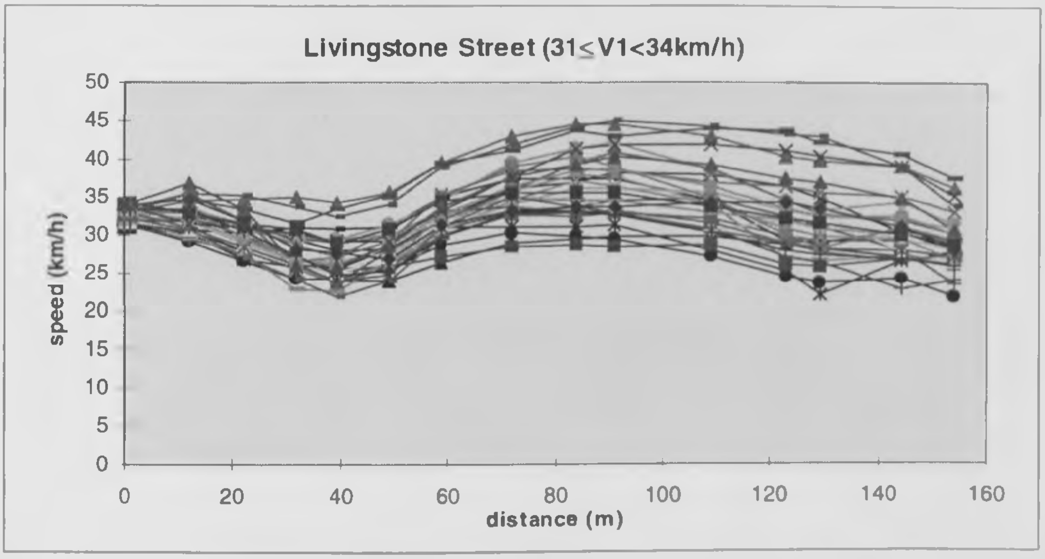


Figure 5.19: Speed profile plots for Livingstone Street (22≤ V1< 30 km/h)





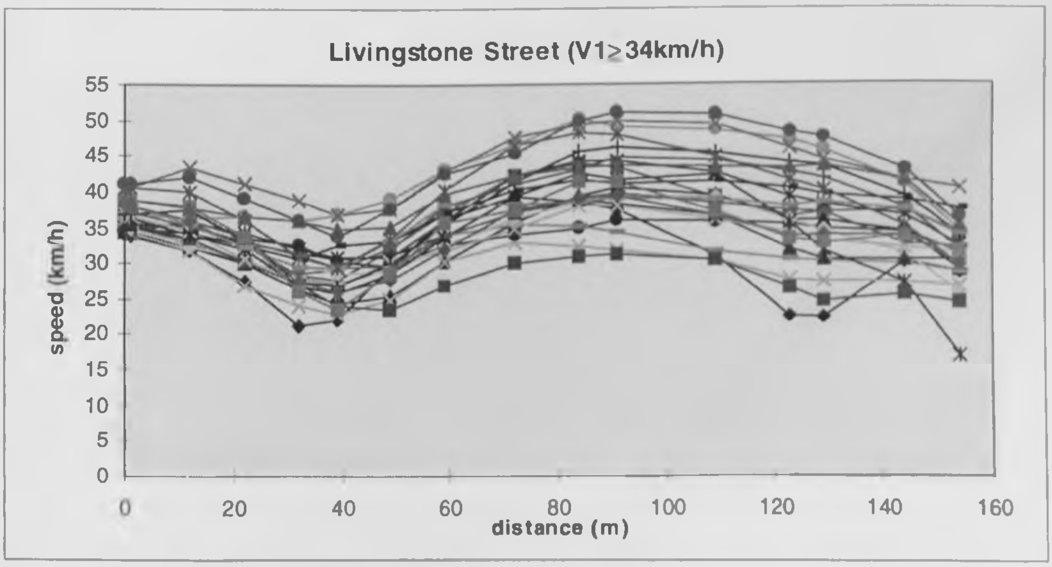


Figure 5.20: Speed profile plots for Livingstone Street (V1≥ 30 km/h)

5.3.4 Discussion

This overview of speed profiles has outlined differences and similarities among the surveyed links and has provided some information on drivers' behaviour. Considering that the sites have different characteristics in terms of the traffic calming scheme therefore making comparisons difficult, the most remarkable similarity among sites is due to the driving style: the higher the speeds the lesser the speed reduction. The entry speed is usually the maximum speed along the link and may explain a proportion of the variance in driver behaviour.

The most remarkable difference among links is associated to the general shape of speed profiles. The three different measures at Foxwood Lane West have produced speed profiles which highlight the peaks and troughs, with the troughs indicating the severity of the measures. The differences in shape become more evident when compared to the relatively flat profiles from the three speed cushions in Foxwood Lane East. Chicanes in Livingstone Street show a distinct profile with a wider curvature and the highest peaks among all sites.

The analysis of average speed at the measures through the descriptive statistics has suggested different impacts according to the type of measure, as mentioned earlier in this chapter. Speed profile plots have enabled the visual examination of the slopes which indicate the acceleration rates between a pair of data points. The slopes also suggest different acceleration rates for different types of measure, reinforcing the statement of differences in impacts by the type of measure.

Comparisons among speed profiles at different sites suggest that the combination of traffic calming measures influences drivers' behaviour and more aggressive and constraining measures reduce speeds to more desired levels. Hence, it appears that speed profile curves can be explained by variables such as the entry speed, the type of measure and the distance between devices.

5.4 Acceleration Profile Overview

This section introduces an overview of the acceleration and deceleration experienced by drivers when crossing traffic calming devices. Acceleration data will be presented as a function of the actual distance between data points. This relationship between acceleration (and deceleration) and distance has been termed an acceleration profile. Acceleration profiles of individual vehicles have been plotted for each site according to the same entry speed bins used for the presentation of speed profiles in the previous section.

5.4.1 Calculation of Acceleration and Deceleration Rates

Acceleration and deceleration profiles have been obtained through conventional equations of motion. According to Papacostas (1987), the velocity of a particle can be expressed as a function of distance:

$$\frac{1}{2}\left(v^2 - v_0^2\right) = a(x - x_0) \qquad (5.1)$$

where: a = acceleration (or deceleration)

v = final speed

v_0 = initial speed

x = distance

This expression has been used for computing acceleration (and deceleration) rate of a vehicle travelling a given distance (from x_0 to x) at constant acceleration (or deceleration) from an initial velocity v_0 to a final velocity v. This expression has been chosen since it does not involve the variable time. The rearrangement of terms of equation 5.1, becomes:

$$a = \frac{v^2 - v_0^2}{2(x - x_0)} \qquad (5.2)$$

Acceleration and deceleration rates have been calculated between each pair of data points for individual vehicles, using equation 5.2, and plotted in relation to the midpoint between the data points. The following sections present the acceleration profiles for the three calibration sites.

Before moving to the acceleration profiles, a brief overview on the acceleration variability has been presented in box plot graphs below (Figures 5.21, 5.22 and 5.23). Values in these graphs refer to maximum, 75th percentile, median, 25th percentile and minimum acceleration rates, grouped by data points. It should be noted that 15 data points are presented since the rates have been obtained between pairs of data points.

Lower and upper limits indicate a great variability in acceleration within the sampled drivers. Commenting on the acceleration/deceleration performance of cars, Lay (1990) reported that an analysis of the standard US urban drive cycle shows that its accelerations and decelerations lie between ± 1.5 m/s^2, however a more realistic assessment of urban driving places the range at ± 3.0 m/s^2. Although this rate seems very high, for instance, it can be found for drivers required to halt when a signal changes. Generally, at all sites, the greatest variability occurs at the link entrance and at the measures. The highest deceleration rates are usually found just before the measures. Actually two acceleration values contain the measure, that is the speed at the measure has been used to obtain acceleration either just before (n-1) or just after (n) the measure. The large size of boxes in Figure 5.21 indicates a high data dispersion just before the hump and the table, higher even taking all measures into account.

The highest dispersion in Foxwood Lane East (Figure 5.22) appears at the link entrance and before the second cushion. Livingstone Street (Figure 5.23) presents high variability also at the end of the link and between chicanes. In contrast the variability before the first chicane is not as large as the remainder of measures.

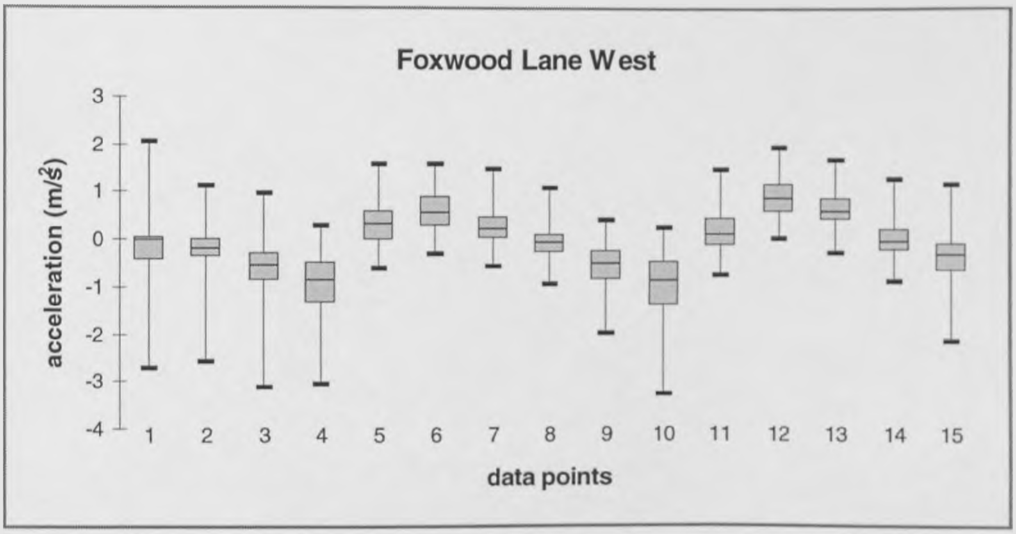


Figure 5.21: Acceleration variability - Foxwood Lane West

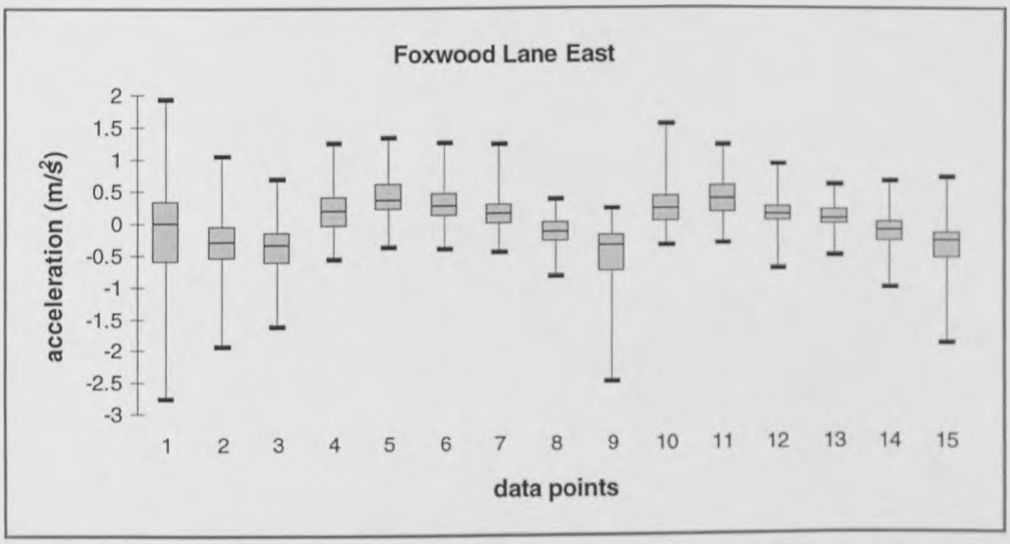


Figure 5.22: Acceleration variability - Foxwood Lane East

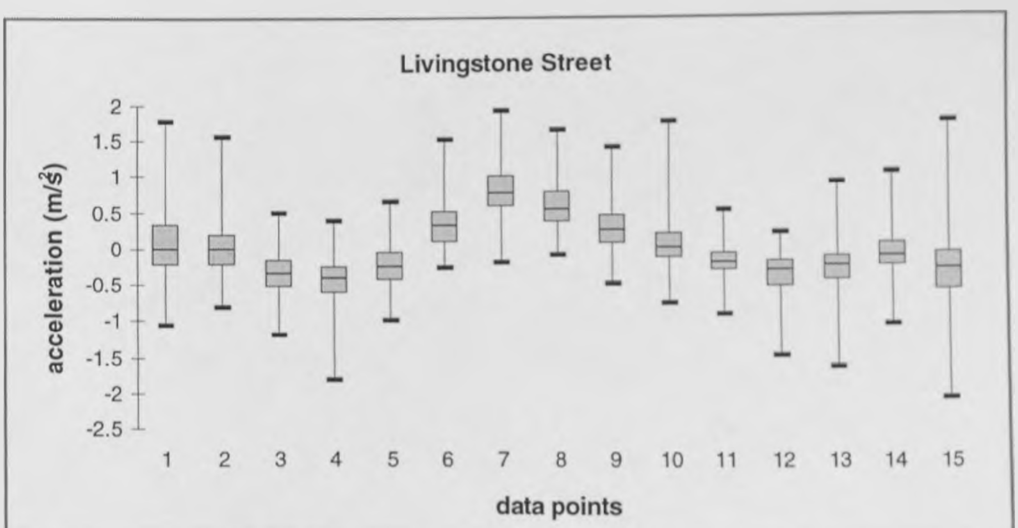


Figure 5.23: Acceleration variability - Livingstone Street

In typical acceleration and deceleration profiles (Figures 3.1 and 3.2 in Chapter 3) when the curve crosses the *x* axis, it indicates maximum or minimum speeds at this point. In this particular case, minimum speed (i.e. when acceleration is zero but increasing) refers to the position of a traffic calming measure in the link. Conversely, the point at which maximum speed is attained can be identified by the point where the acceleration profile crosses the *x* axis but is falling, therefore, indicating the transition from the acceleration phase to a deceleration one.

5.4.2 Foxwood Lane West Acceleration Profiles

In the following acceleration profile plots (Figures 5.24 and 5.25), the positions of the hump and the table are easily associated with the convergence of lines towards zero when the deceleration phase stops and the acceleration one starts. Acceleration profiles follow a general pattern and similar variation (dispersion of values) for different entry speeds, nevertheless different patterns are more frequent in lower (< 30 km/h) and higher (> 45 km/h) speed bins. The highest deceleration rates occur at the approach to the table (second calming measure) whereas the lowest one refers to the cushion (last measure). Usually the highest acceleration rates are found before the cushion, however similar high acceleration rates also precede the hump for entry speed bins greater than 40 Km/h.

There is a general trend indicating a quick change from the position of maximum deceleration to a subsequent maximum acceleration in the vicinities of the calming measures. On the other hand, the change from maximum acceleration to maximum deceleration in the vicinities of the point of maximum speed, takes longer to happen. In other words, the rate at which acceleration increases is greater than the rate at which it falls. The great majority of vehicles crossed the first and second sensor at constant speed or within small speed variations, represented by the first data point in the graphs. The range of these values usually vary from 1.0 to -1.0 m/s^2. The majority of vehicles present a negative value indicating that the deceleration phase has already started. Accelerations outside this range (approximately 10% of all observations) are more frequent for entry speeds greater than 36 km/h.

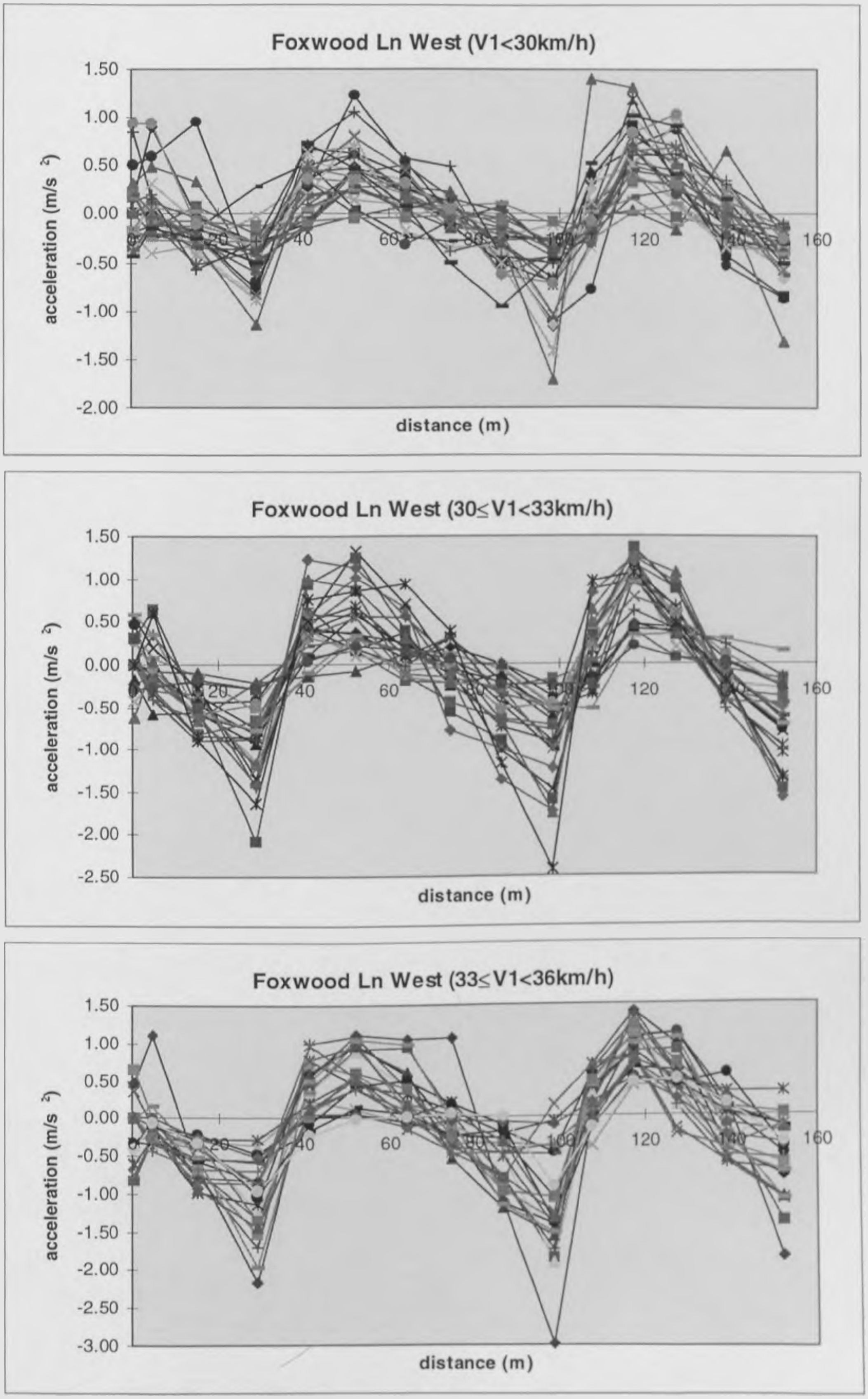
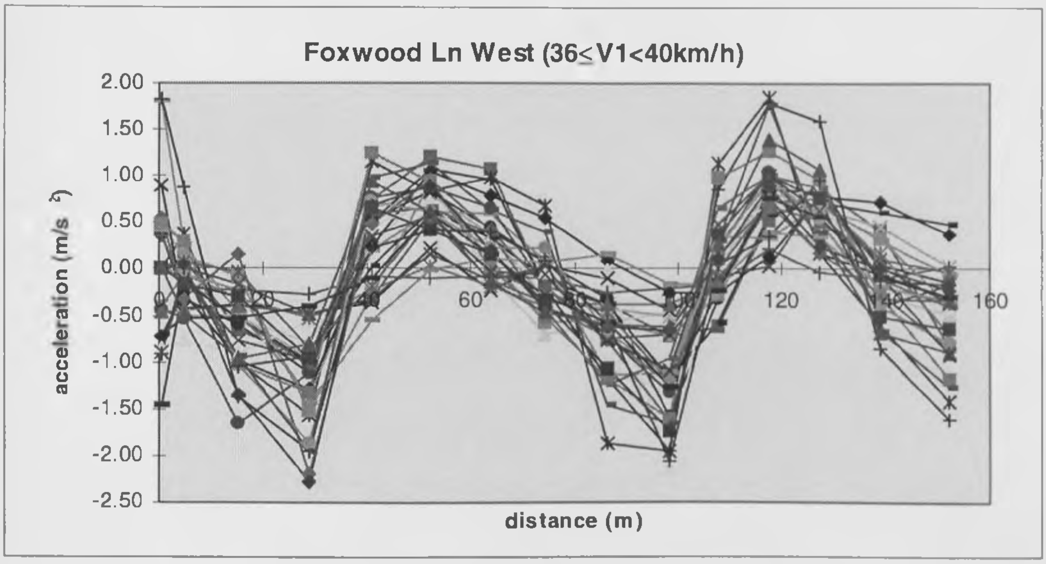
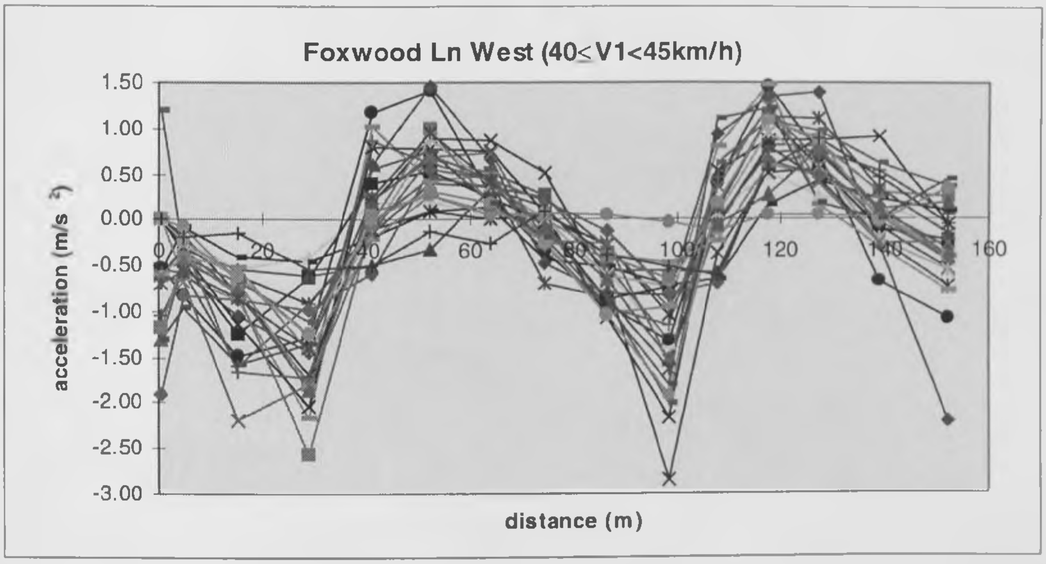


Figure 5.24: Acceleration Profiles - Foxwood Lane West (V1<36 km/h)





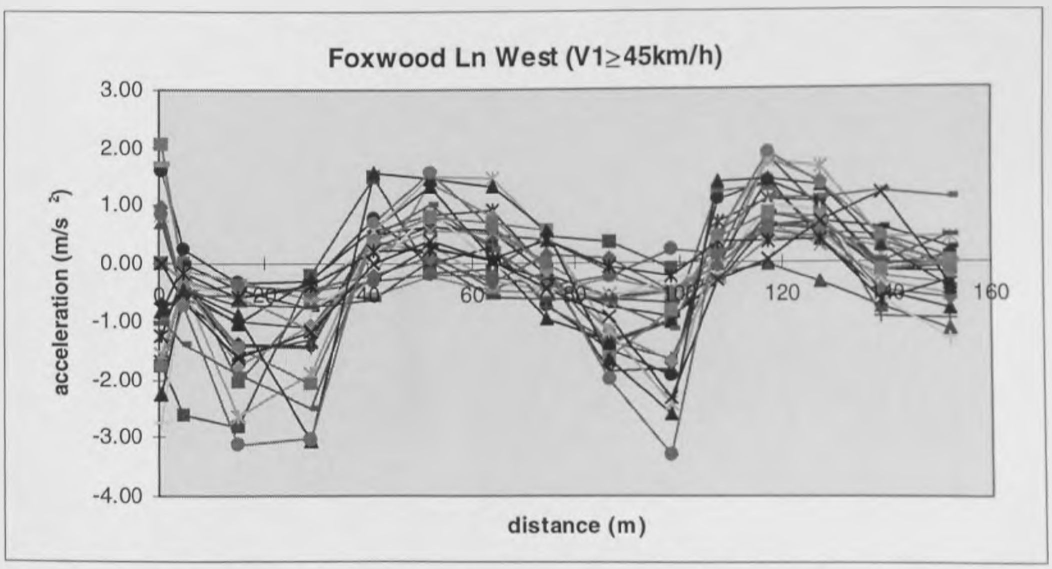


Figure 5.25: Acceleration Profiles - Foxwood Lane West (V1≥ 36 km/h)

5.4.3 Foxwood Lane East Acceleration Profiles

In the following acceleration profile plots for Foxwood Lane East (Figures 5.26, 5.27 and 5.28), the position of the first and second cushion can also be associated with the convergence of lines towards zero (crossing x axis and increasing).

Deceleration and acceleration rates are quite similar at the approach and exit for all cushions, and extreme rates reveal unusual driver behaviour. The dispersion of those values is noticeably smaller than Foxwood Lane West. Moreover, when disregarding extreme odd values, acceleration profiles for different entry speeds are quite similar. Comparing all different profiles, the acceleration rate variation for vehicles entering the link at speeds greater than 42 km/h appears less accentuated, resulting in smoother curves. Sudden changes in acceleration and deceleration can be observed at about 140 m in all graphs, which correspond to the area of maximum speed, resulting in disturbances to the general profile pattern.

The majority of entry acceleration/deceleration rates lies again within 1.0 and -1.0 m/s^2, and the highest variability is accounted for higher entry speeds ($\geq$ 42 km/h).

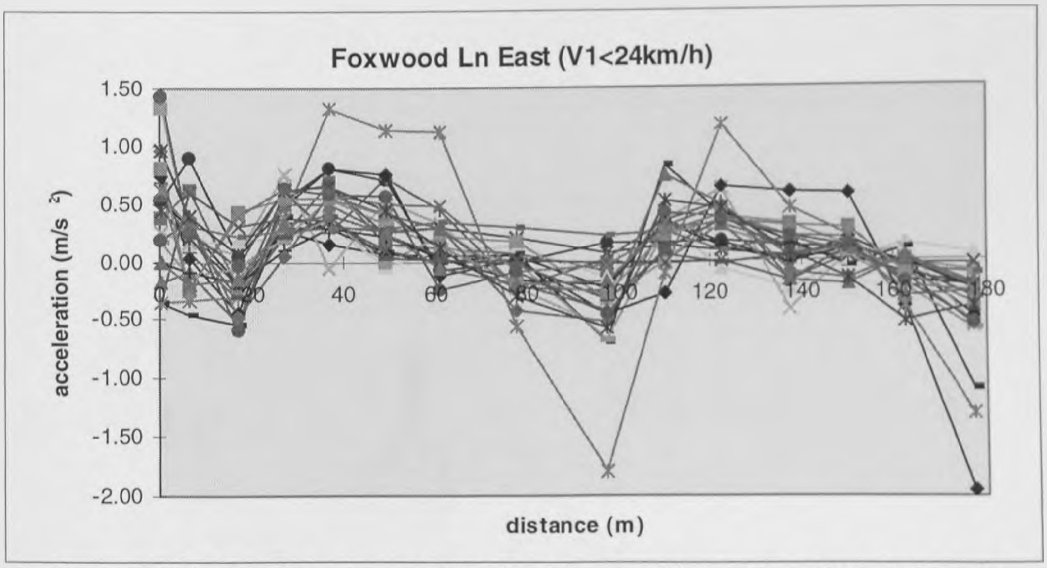


Figure 5.26: Acceleration profiles for Foxwood Lane East (V1< 24 km/h)

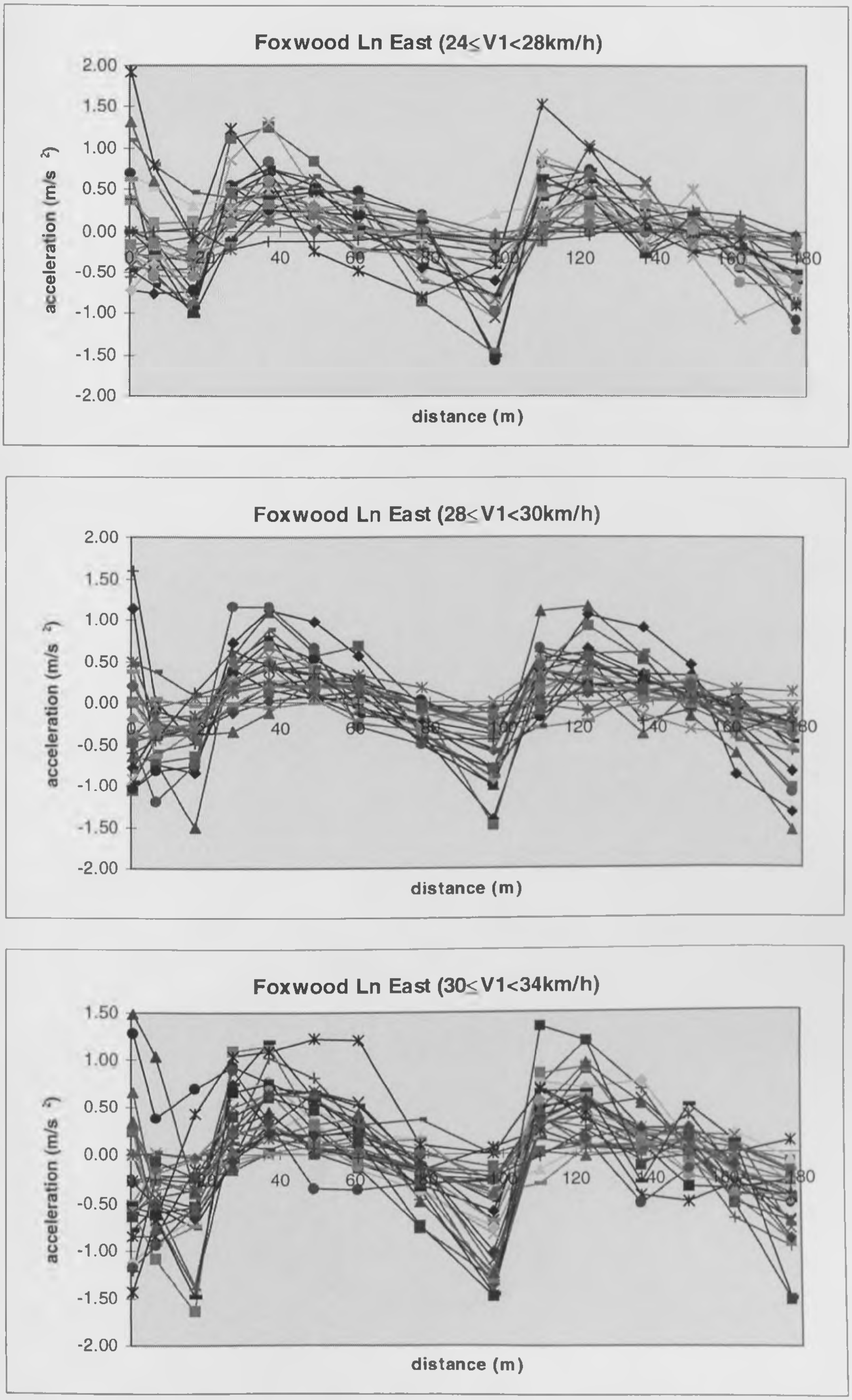


Figure 5.27: Acceleration profiles for Foxwood Lane East (24 ≤ V1 < 34 km/h)

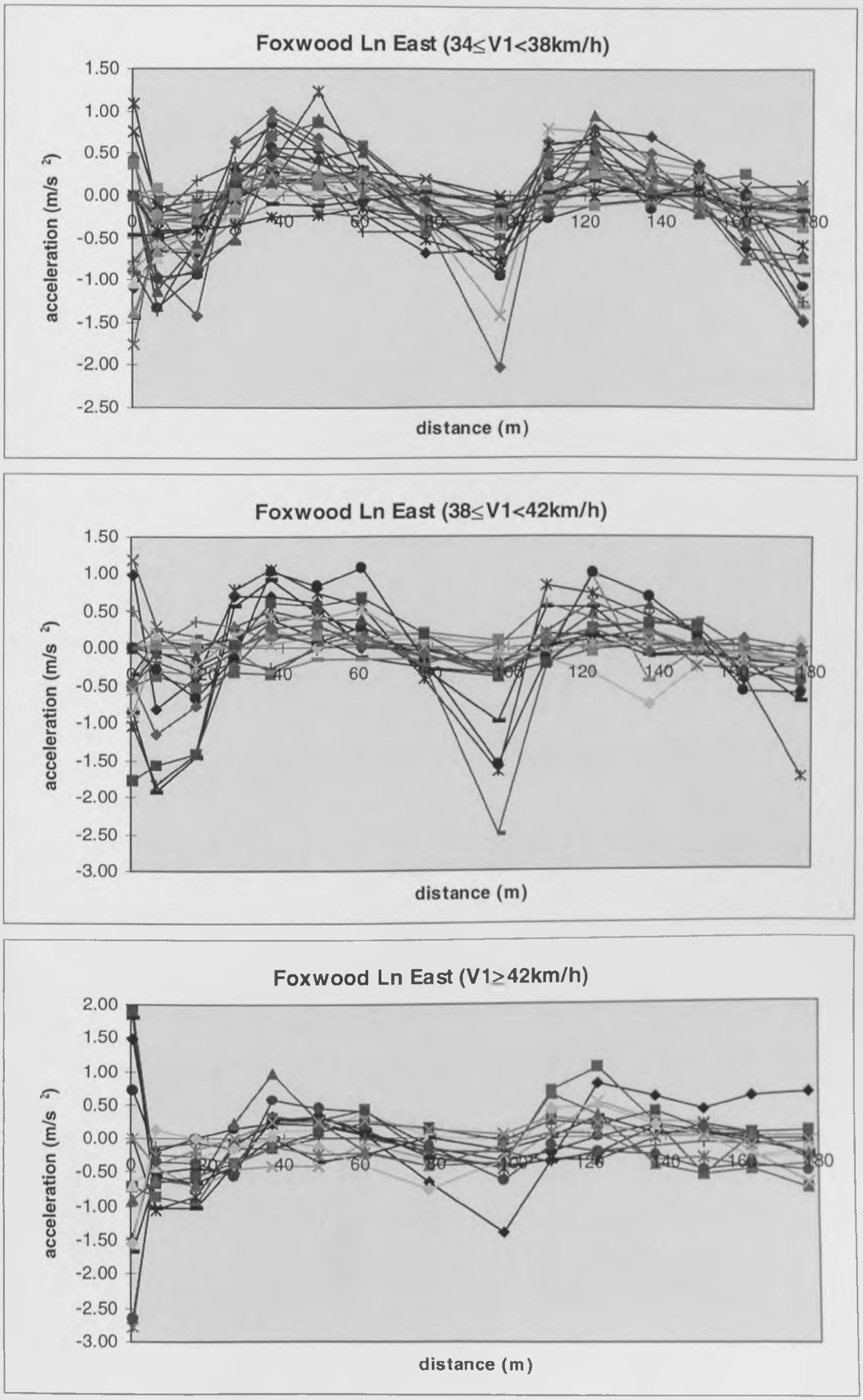


Figure 5.28: Acceleration profiles for Foxwood Lane East (V1≥ 34 km/h)

5.4.4 Livingstone Street Acceleration Profiles

Following the same procedure to identify the position of chicanes in the acceleration profiles (Figure 5.29, 5.30 and 5.31) along Livingstone Street, the first chicane is easily associated with the convergence of lines, whereas the position of the second one (129.1 m from the origin) is not so clear because the driving style varies greatly at the end of the link. At this point either a continuous deceleration which is the average trend, or a slight acceleration after the second chicane can be observed. The first chicane registers higher deceleration rates in comparison to the second one.

Acceleration profiles are similar for all entry speed bins. Odd acceleration values usually occur in the vicinity of the second chicane. Acceleration rates at the link entrance are more uniform than the previous sites.

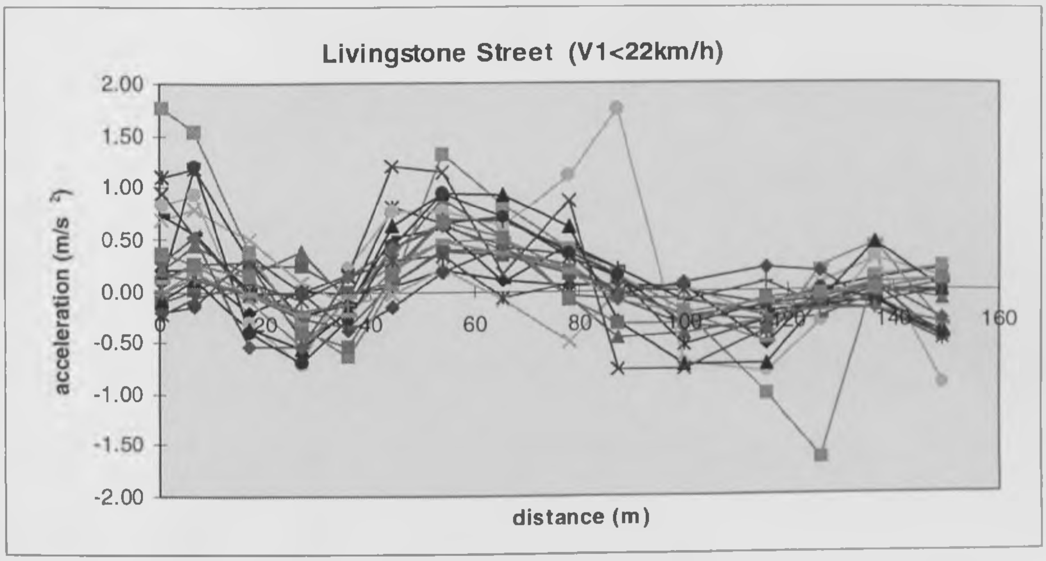


Figure 5.29: Acceleration profiles for Livingstone Street (V1 < 22 km/h)

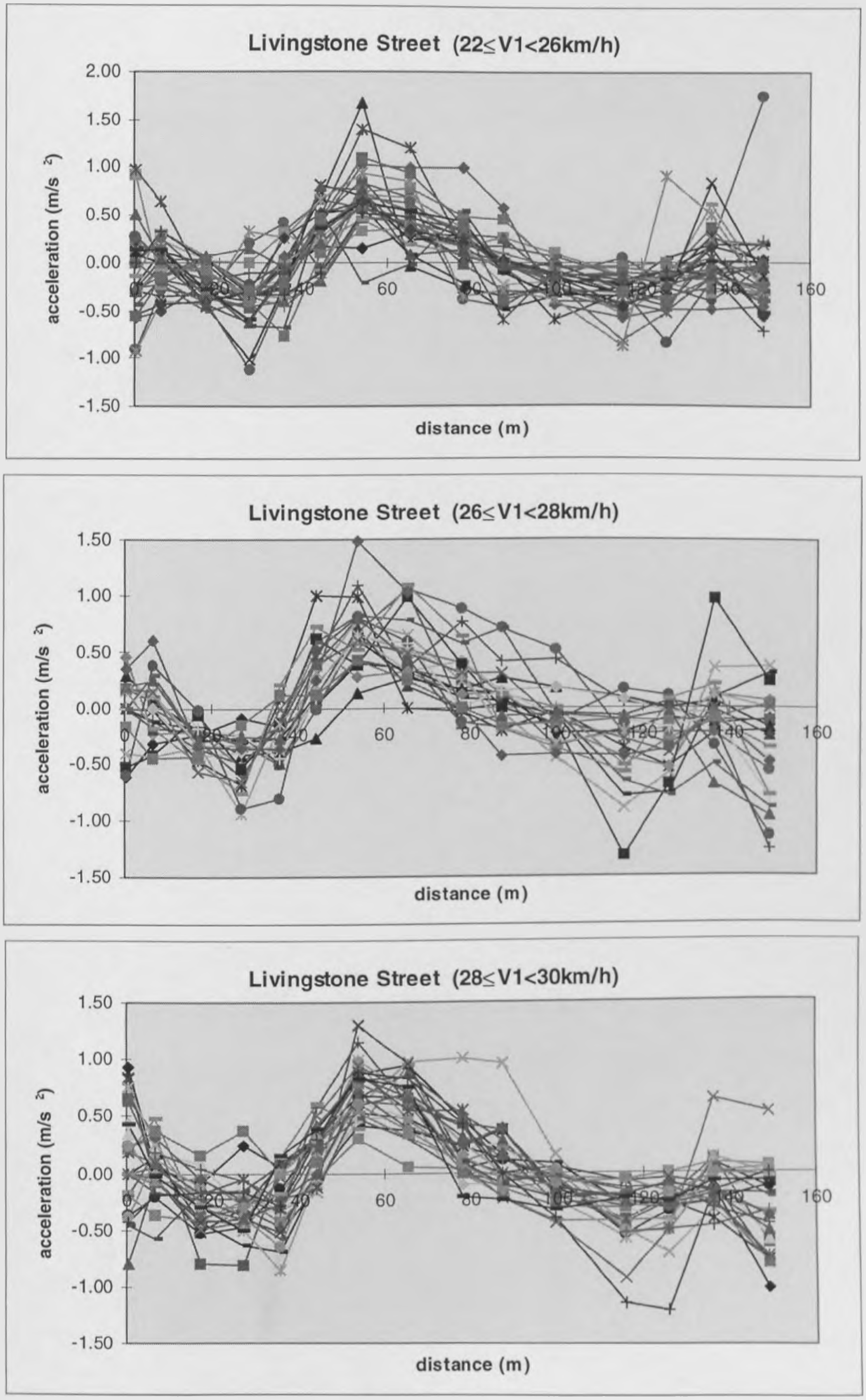


Figure 5.30: Acceleration profiles for Livingstone Street (22 ≤ V1< 30 km/h)

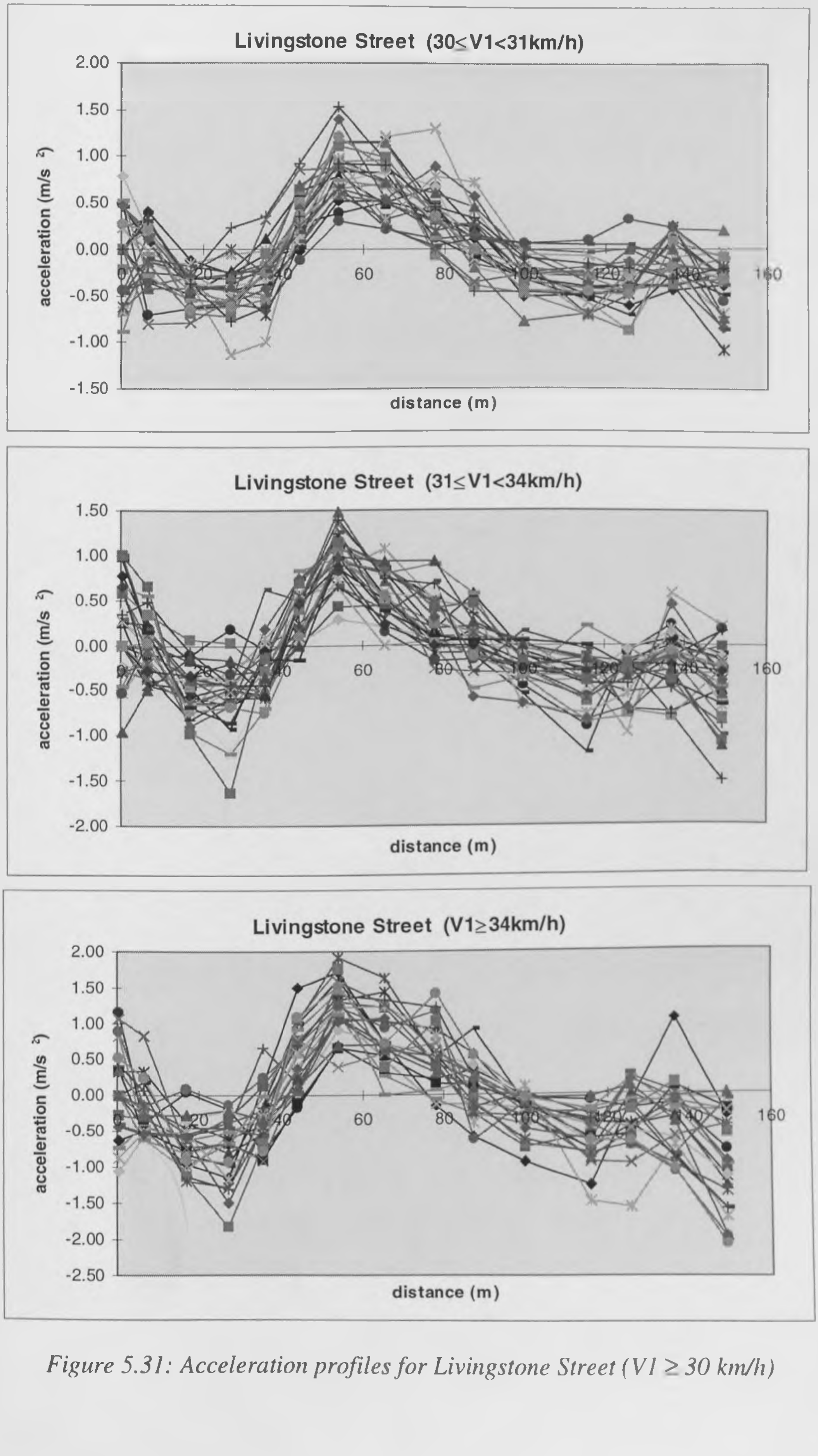


Figure 5.31: Acceleration profiles for Livingstone Street (V1 ≥ 30 km/h)

5.4.5 Discussion

The acceleration and deceleration rates found for the survey sites seem to be in accordance with the figures reported by Lay (1990) for the UK mean rates: 0.5 m/s^2 for acceleration and 0.8 m/s^2 for deceleration.

The position of traffic calming measures in the surveyed links can be associated to the trend of lines converging to zero and acceleration increasing (change of phase from deceleration to acceleration) in acceleration profiles. Similarly, the position at which maximum speed is attained can also be associated to the trend of lines converging to zero with acceleration falling. The convergence is more accentuated for the Foxwood Lane West profiles, perhaps reflecting more uniform driver behaviour, in contrast to the fuzzy profiles surrounding the second chicane in Livingstone Street.

A common manoeuvre can be observed at all sites: the maximum deceleration occurs before the measure, the deceleration continues up to the measure, when the acceleration phase starts. Moreover, the rate at which acceleration increases is greater than the rate at which it falls.

Examination of acceleration profiles also suggests that different types of measures generate different acceleration and deceleration rates.

5.5 Hypothesis Formulation

This first examination of data has been conducted in two parts, the first one dealing with descriptive statistics of data grouped by the data points, and the second part has focused on drivers' behaviour through the analysis of speed and acceleration profiles for individual vehicles. This first data analysis has raised some issues concerning the performance of the traffic calming measures described next.

Speed profiles have been represented as a relationship between speed and distance. A generic graphical representation of a speed profile is shown in Figure 5.32.

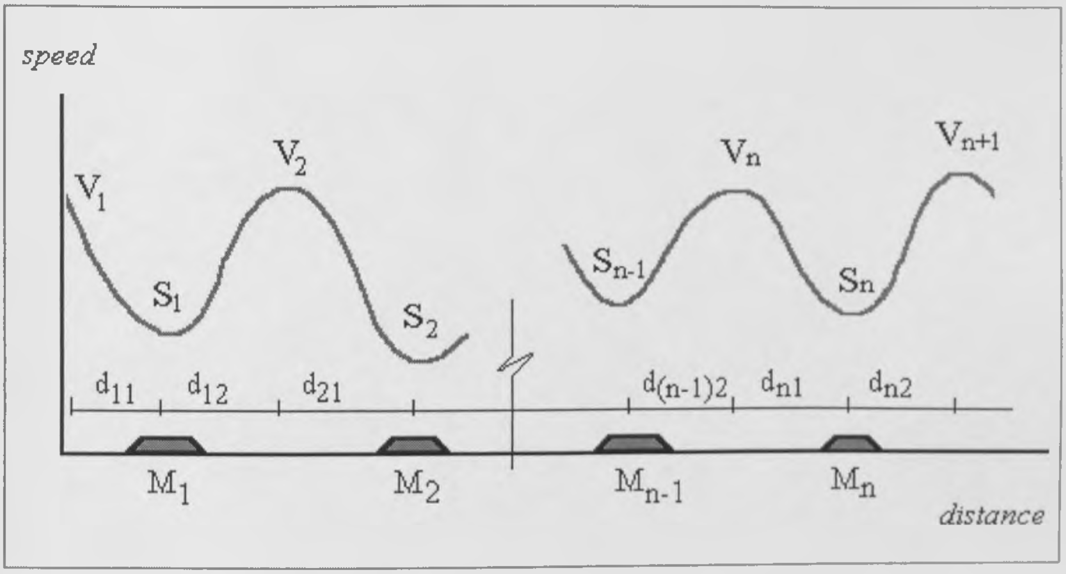


Figure 5.32: Generic speed profile representation

Key: n = order of the measure in the sequence

V_n = maximum speed (input speed) preceding measure n

M_n = the type of measure at n

S_n = minimum speed on passing measure n

d_{n1} = distance from V_n to S_n

d_{n2} = distance from S_n to V_{n+1}

d_n = distance from measure (n-1) to measure n = $d_{(n-1)2} + d_{n1}$

In view of that a starting point to data analysis might be the assumption: if minimum speed (S) is a function of the type of measure (M), the input speed (V) and the distance (d), the following relationship can be developed:

$$S_n = f\,(V_n, M_n, d_{n1})$$

Concerning maximum speeds, the following relationship can be hypothesised:

$$V_{n+1} = f\,(S_n, d_{n2})$$

This general approach has led to pertinent issues which will be verified in the subsequent chapters, such as:

a) whether the effect of any one measure is consistent wherever it occurs;

b) whether measures in sequence produce an additive effect on speeds;

c) whether drivers exhibiting different behaviour (through their input speeds) respond in different ways to the measures;

d) the effects if any of the input speed upon the effectiveness of the measures;

e) whether the minimum speed is a function of the type of measure, the input speed and the distance;

f) whether the maximum speed is a function of the minimum speed at the upstream measure and the distance or whether it is also affected by the downstream measure;

g) the likely point to attain the maximum speed between measures; and

h) the likely point to achieve the minimum speed, initially assumed to be at the measure.

Other pertinent issues, not related to the above relationships, will also be investigated in the subsequent chapters as follows:

i) the effect if any of the deceleration rate upon the minimum speed and the effect of the acceleration rate upon the maximum speed;

j) whether the acceleration and deceleration rates are a function of the type of measure;

k) whether travel time in calmed links may be determined by the input speed;

l) the likely delay (increase in travel time) according to the type of measure; and

m) whether drivers speed up after passing traffic calming devices as an attempt to recover the resultant time loss.

CHAPTER 6

HYPOTHESIS TESTING

The main focus of this chapter is directed towards the investigation of the hypotheses derived in the previous chapter. This chapter has been divided into three main sections namely: (i) the consistency of the impacts of measures, (ii) acceleration and deceleration rates observed during the negotiation of the measures, and (iii) issues on travel times along calmed links. Each one of these parts relates to the investigation of hypotheses listed in the previous chapter so that, the first part deals with hypotheses *a, b, c, d, e* and *f*; the second part *g, h, i* and *j*; and *k* and *l* in the third part. The investigation of hypothesis *m,* which refers to drivers speeding up after travelling along a traffic calmed area, has been presented in Appendix A because its inclusion here would have disrupted the thesis flow since it is based on a different data set in addition to referring to different sites.

6.1 Consistency of Impact of Measures

The analysis to be conducted in this section aims at investigating the following hypotheses:

a) whether the effect of any one measure is consistent wherever it occurs;

b) whether measures in sequence produce an additive effect on speeds;

c) whether drivers exhibiting different behaviour (through their input speeds) respond in different ways to the measures;

d) the effects, if any, of the input speed upon the effectiveness of the measures;

e) whether the minimum speed is a function of the type of measure, the input speed and the distance; and

f) whether the maximum speed is a function of the minimum speed at the measure and the distance.

Data examination carried out in the previous chapter has pointed out issues concerned with the impact of traffic calming measures. It seems that different measures can generate different impacts. This has led to the assessment of impacts resulting from the same type of measure in order to investigate the consistency of a measure, that is whether the impact of a measure is identical at any site.

The first step to verify the consistency of measures is to test if the mean speed crossing one measure is equal to the mean at any other one, using a t-test for two samples. T-tests can be one or two-tailed. One tailed tests are usually applied to situations at which the two means are expected to be different, for instance before and after studies to analyse the effect of a speed control device. Therefore, in this case t-tests were two-tailed as there is no good reason to be suspicious of computed values on only one side. F-tests have been conducted to test the difference in dispersion (variance) among samples, to devise the more appropriate t-test. The F-test has indicated whether the t-test assuming unequal (also referred to as a heteroscedastic t-test) or equal variance would be more suitable. The 'Excel' statistical analysis tool was used to conduct these tests.

The second step also involved two-tailed t-tests to assess the equivalence of maximum speeds recorded between two measures. Finally, the third step consisted of establishing relationships for maximum speed downstream (V_{maxD}) and upstream (V_{maxU}) of a measure, and for minimum speed (V_{min}). These speeds are respectively taken: (a) at the point at which vehicles attained the maximum speed upstream and downstream of traffic calming measures and (b) at the traffic calming measure. Relationships between maximum and minimum speed have been obtained through linear regression analysis also using the 'Excel' analysis package.

6.1.1 Testing the Equivalence of Means for Speed Cushions

There are four speed cushions among the calibration sites, three at Foxwood Lane East and one at Foxwood Lane West which will be designated as V4, V10, V16 and $V16_w$

respectively. The letter ($_w$) stands for West to differentiate the two cushions at the same position (V16) in Foxwood Lane East and Foxwood Lane West.

Before conducting the t-tests among all pairs of cushions, the equivalence of variances was tested using the F-test in which the null hypothesis asserts the equivalence of variances. The results indicate equal variances for the following pairs: V4 - V16$_w$, V10 - V16 and V10 - V16$_w$. Therefore, for these pairs a t-test assuming equal variance has been applied and t-tests assuming unequal variance for the remainder of pairs of cushions. The main difference between these two tests relates to the formula used to approximate the degrees of freedom. The result of the calculation is usually not an integer. The nearest integer is used to obtain a critical value from the t table. T-tests have been conducted in order to verify the following hypotheses:

$$H_0 : \mu_1 = \mu_2$$

$$H_1 : \mu_1 <> \mu_2$$

The null hypothesis asserts that the two means are in fact the same, while the alternative hypothesis H_1 asserts that one mean is greater than the other one. Table 6.1 presents the statistics for the t-tests conducted for the 95 per cent confidence interval.

Table 6.1 : Summary of t-tests for cushions

CUSHION	MEAN	VARIANCE	CASES	DF	t stat	t critical
V4	28.51	62.35	172	340	0.388	1.967
V10	28.17	72.41	172			
V4	28.51	62.35	172	342	-0.006	1.967
V16	28.52	65.78	172			
V4	28.51	62.35	172	323	0.695	1.967
V16$_w$	27.90	61.81	153			
V10	28.17	72.41	172	342	-0.389	1.967
V16	28.52	65.78	172			
V10	28.17	72.41	172	323	0.291	1.967
V16$_w$	27.90	61.81	153			
V16	28.51	65.78	172	321	-0.692	1.967
V16$_w$	27.90	61.81	153			

The comparison of t statistic and t critical values in Table 6.1 has led to the acceptance of the null hypothesis i.e. there is no conclusive evidence on which to reject the equivalence of means when testing the means at speed cushions.

6.1.2 Testing the Equivalence of Means for Chicanes

The same procedures carried out to test the equivalence of means at speed cushions have been carried out for the two chicanes in Livingstone Street. F-tests have also been conducted and have demonstrated that the variances are not equal. Therefore, the same t-test null hypothesis has been tested by means of the t-test for two samples assuming unequal variances.

The reference was taken as the chicanes midpoint V6 and V14 for the first and second chicanes respectively. The test summary is shown in Table 6.2 below. The comparison of t stat and t critical values results in the rejection of the null hypothesis.

Table 6.2: Summary of t-test for chicanes in Livingstone Street

CHICANE	MEAN	VARIANCE	CASES	DF	t stat	t critical
V6	24.28	18.94	179	321	-9.495	1.967
V14	29.61	37.58	179			

6.1.3 Testing the Equivalence of Means for Maximum Speed (between measures)

The previous sections have focused on minimum speeds at the devices. This section aims at a first examination of the maximum speeds recorded between traffic calming measures, in order to indicate the likely variable(s) which may affect maximum speeds.

Table 6.3 shows for each survey site, the data points taken as the reference for maximum speed (between measures) and also for minimum speed (at the measure) which will be also used in the following section. The determination of the data point at which the maximum speed is attained has been based on the average speed calculated for each data point, even though not all vehicles attained maximum speed at that data point, as can be seen in the speed profile plots in the previous chapter.

Table 6.3: Maximum and minimum speed data points

DATA POINTS / SITES	Vmax	Vmin	Vmax	Vmin	Vmax	Vmin
Foxwood Ln East	V1	V4	V8	V10	V14	V16
Foxwood Ln West	V1	V5	V8	V11	V14	V16
Livingstone Street	V1	V6	V11	V14	--	--

The equivalence of means has been verified through t-tests. Before conducting these tests, F-tests were again carried out to determine whether variances were equal and therefore, to indicate the most appropriate t-test. Equivalence of means has been firstly tested within sites for all possible combinations of maximum speeds. Table 6.4 presents the summary of t-tests. It should be stressed that this table only includes the t-tests of pairs of data points which showed no significant difference at the 95% confidence level for maximum speeds. Comparisons involving V14 (FW) should be assessed with care because strictly data for this point could not be accepted as normally distributed.

Table 6.4: Summary of t-tests for the equivalence of maximum speeds within sites

Speed	Mean	Variance	Cases	DF	t_{stat}	$t_{critical}$
V8 (FE)	33.68	39.01	172	341	1.177	1.967
V14 (FE)	32.86	43.88	172			
V1 (FE)	31.78	56.21	172	342	-1.408	1.967
V14 (FE)	32.86	43.88	172			
$V8_w$ (FW)	32.53	37.27	153	303	1.650	1.968
$V14_w$ (FW)	31.36	33.49	153			

Key: FW = Foxwood Lane West; FE = Foxwood Lane East

In order to examine speeds between measures fully, t-tests have also been applied to compare maximum speeds among the calibration sites. Equivalence of means has been tested between all combinations of maximum speed data points. However, for the sake of simplification only the equivalences confirmed through the statistical tests are shown in Table 6.5 below.

Table 6.5: T-test for the equivalence of maximum speeds among calibration sites

Speed	Mean	Variance	Cases	DF	t_{stat}	$t_{critical}$
V11 (LIV)	34.12	33.48	179	344	0.687	1.967
V8 (FE)	33.68	39.01	172			
V11 (LIV)	34.12	33.48	179	339	1.893	1.967
V14 (FE)	32.86	43.88	172			
V8 (FE)	33.68	39.01	172	323	1.674	1.967
V8 (FW)	32.53	37.27	153			
V1 (FE)	31.78	56.21	172	317	0.567	1.967
V14 (FW)	31.36	33.49	153			
V1 (FE)	31.78	56.21	172	321	-0.982	1.967
V8 (FW)	32.53	37.27	153			

Key: FW = Foxwood Lane West; FE = Foxwood Lane East; LIV = Livingstone Street

6.1.4 Maximum and Minimum Speed Relationships for Individual Measures

The comparison of mean speeds at the measures and between measures carried out in the previous two sections, has pointed out similarities and differences among measures. The consistency of impacts of measures will also be verified by the comparison of relationships established between maximum and minimum speeds. The purpose of this study is to verify the consistency of these relationships among measures in addition to establishing new useful relationships that describe the effectiveness of each measure, that is the actual speed at the measure in relation to the maximum speed upstream of it and the maximum speed downstream of a measure in relation to the speed at that measure.

This study has been undertaken for the three calibration sites. As mentioned before, the maximum and minimum speed data points are shown in Table 6.3. Minimum speed was taken as the speed at the traffic calming measure.

Two approaches have been considered to study the relationships between maximum and minimum speed along a traffic calmed link:

a) $V_{maxD} = f(V_{min})$

where V_{maxD} is the maximum speed downstream of a measure

V_{min} is the minimum speed at the measure; and

b) $V_{min} = f(V_{maxU})$

where V_{min} is the minimum speed at the measure

V_{maxU} is the maximum speed (input speed) before negotiating a measure.

Regression analysis was used to obtain a linear relationship between maximum and minimum speeds of the form: $Y = a + bx$. The analysis of significance of the regression coefficients, in a few cases, has pointed out the need to re-run the regression analysis adopting the constant term equal to zero since the absolute t_{stat} value found for the constant coefficient is less than 1.960 ($t_{critical}$ for the 95% confidence level) indicating that the coefficient does not contribute to the model explanation.

To facilitate the analysis, the relationships have been grouped according to the nature of the relationship. Table 6.6 displays the relationships of downstream speed (V_{maxD}) as a function of the speed at the measure (V_{min}) and Table 6.7, the speed at the measure (V_{min}) as a function of the input speed (V_{maxU}).

Maximum Speeds

Referring to Table 6.6, Foxwood Lane East and Foxwood Lane West present similar coefficients. In general, they indicate that maximum speed between measures is approximately equal to 60% of the speed at the measure plus 14 to 17 km/h. Nevertheless, the analysis of these roads individually, shows relationships yet more similar. Similarities in the relationships are expected especially in Foxwood Lane East because measures of the same type are under consideration. However the devices at V5 (hump) and V11(table) in Foxwood Lane West are not of the same type but they yielded similar relationships. The coefficients found for Livingstone Street differ from the rest and indicate an increase of about 10 km/h in the downstream speed in relation to the speed at the first chicane.

Because distance between measures vary, it proved easier to compare maximum speeds in terms of the percentage of the distance between measures at which they occurred (percentages are shown in brackets in Table 6.6).

Table 6.6 Relationships for maximum speed between measures

Foxwood Ln East	Foxwood Ln West	Livingstone Street
$V_8 = 15.29 + 0.65\ V_4$ $R^2 = 0.664$ [53%]	$V_8 = 15.91 + 0.62\ V_5$ $R^2 = 0.572$ [51%]	$V_{11} = 10.01 + 0.99\ V_6$ $R^2 = 0.558$ [58%]
$V_{14} = 14.18 + 0.66\ V_{10}$ $R^2 = 0.725$ [63%]	$V_{14} = 16.97 + 0.61\ V_{11}$ $R^2 = 0.582$ [52%]	

key: [ ] = percentage of the distance between measures at which maximum speed occurred.

In view of the above, it appears that speed at the device has a greater impact on downstream maximum speeds than the distance, although strictly this cannot be assessed using solely the within site data. This issue can be illustrated with the following comparisons using the position of the maximum speed described as a percentage of the inter-measures spacing:

a) Foxwood Ln West and East present similar relationships for V8. The previous section has indicated the equivalence of these speeds. Distances between measures are not similar but the maximum speeds occur at similar percentages of the distance between measures;

b) the maximum speed for V8 (Foxwood Ln West) is equivalent to V14 (Foxwood Ln West), however distances and upstream measures are not equal, but the relationships and locations of the maximum speed points are similar;

c) V8 and V14 (Foxwood Ln East) present similar distances and relationships, and also the same type of measure indicating similar effects of the distance and the speed at the device, but the locations of the maximum speed points differ.

Nevertheless, average speed at V13 is almost equal to V14, and V13 corresponds to 50% of the inter-measure spacing.

Hence, those relationships suggest that maximum speed is a function of the speed at the previous measure in addition to distance. In fact, distance is better described as the percentage of the spacing between measures at which maximum speed is attained. It appears that the type of measure is not important in influencing maximum speed; however, the speed at the device is a consequence of the type of measure.

Minimum Speeds

Table 6.7 presents the relationships derived for the speed at the measure (V_{min}) as a function of the maximum (input) speed upstream of the measure. V4, V10, V16 in Foxwood Lane East and V16 in Foxwood Lane West refer to the same type of measure, speed cushions. Apart from V4, for which relationships pass through the origin, the similarity of coefficients and signs of the relationships is remarkable especially between the cushions V16 (at Foxwood Lane West and Foxwood Lane East). Despite having different upstream measures and maximum upstream speeds, the cushions in question are accounting for similar reductions in speeds. Cushion V4 presents a quite different relationship that may result from the particular position of the first sensor (at V1) as explained earlier and, therefore, this relationship should not have the same weight as the others during the overall comparison.

Table 6.7: Relationships for the speed at the measure

Foxwood Ln East	Foxwood Ln West	Livingstone Street
$V_4 = 0.90\ V_1$ $R^2 = 0.738$	$V_5 = 0.73\ V_1$ $R^2 = 0.494$	$V_6 = 7.99 + 0.57\ V_1$ $R^2 = 0.420$
$V_{10} = -8.27 + 1.08\ V_8$ $R^2 = 0.631$	$V_{11} = 0.73\ V_8$ $R^2 = 0.433$	$V_{14} = 0.87\ V_{11}$ $R^2 = 0.737$
$V_{16} = -6.45 + 1.06\ V_{14}$ $R^2 = 0.756$	$V_{16} = -5.66 + 1.07\ V_{14}$ $R^2 = 0.620$	

With regard to the reduction in speed, the relationships established for the hump (V5) and the table (V11) in Foxwood Lane West indicate the same proportion of speed reduction (around 30%), which could also be an indication of the same effect of different types of measure. In this connection, the equivalence of means has been verified through a t-test. According to the statistics displayed in Table 6.8 the hypothesis of equivalence between means has been rejected indicating that the means are not equal.

Table 6.8: T-test statistics for the hump and the table in Foxwood Lane West

Measure	Mean	Variance	Cases	DF	t stat	t critical
V5 hump	26.62	54.76	153	304	3.493	1.968
V11 table	23.69	52.82	153			

Livingstone Street data presents peculiar relationships for the two chicanes in the sense that V6 produces a higher speed at the measure than the entry speed (V1) for values less than 18.58 km/h. Moreover, it accounts for smaller speed reductions in comparison to V14 for speed values less than 27 km/h, and the other way round for higher speed values.

In summary the analysis of these relationships for minimum speeds has shown that:

a) cushions show similar speed reduction in spite of differences in upstream measure as well as in distance from the upstream measure and the location of the maximum speed point;

b) hump and table also show similar speed reductions, similar distance from the upstream measures as well as the location of maximum speed point; and

c) chicanes present differences in the relationships and distances from the upstream measure, and according to the t-test the impact of the chicanes on speed cannot be accepted as equivalent to each other.

Although these findings cannot be treated as conclusive, they indicate that the type of device is the main variable affecting minimum speeds in addition to the maximum speed upstream of the measure and the location of the maximum speed expressed as a percentage of the distance between measures.

6.1.5 Discussion

The effect of any one measure being consistent wherever it occurs could not be fully tested since the traffic calming measures at the validation sites were not included in this analysis. From the comparisons which were carried out, speed cushions have shown similar effects on speeds at the devices, whereas the same cannot be said about the chicanes, possibly as a result of their design and geometry. Off-road trials conducted by Sayer and Parry (1994) determined the relative effects on vehicle speed of changing the physical dimensions of the chicanes. Although the absolute values may not necessarily represent what would be achieved on the public road, they found some evidence of different impacts on speeds due to different combinations of stagger lengths and free view width. In terms of design, the table and the hump at Foxwood Lane West present the same device height but different profiles (the hump has a circular profile and the table a flat one) and their effect on speeds could not be accepted as equal as shown in Table 6.8.

It is unlikely that measures in sequence produce an additive effect on speeds. Firstly, cushions in sequence in Foxwood Lane East have shown similar speeds. The effect of the table being more accentuated than the hump (Foxwood Lane West) could have suggested that there is an additive effect, but the measures under consideration are not of the same type, moreover the speed at the following cushion is similar to those at Foxwood Lane East. The chicanes could rather have suggested the opposite effect: once a measure perceived as a strong speed reduction factor has been negotiated, its impact could decrease, resulting in higher speeds at the following measure, presumably as a result of their design.

Whether drivers exhibiting different behaviour (determined through their input speeds) respond in different ways to the measures has been analysed by the relationships established between the input (entry) speed and the speed at the first calming measure. These relationships have demonstrated a certain uniform response indicating similar behaviour irrespective of the input speed. However, a degree of variability was also detected, and it is indicated by the R^2 values of those relationships 0.42, 0.49 and 0.74, respectively for Livingstone Street, Foxwood Lane West and Foxwood Lane East. Therefore, based on the correlation coefficient values, it can be concluded that there is a certain pattern of behaviour, but several drivers do not follow that pattern and respond in different ways to the measures, especially at Livingstone Street and Foxwood Lane West.

The effect of the input speed upon the effectiveness of the measures can be analysed by the relationships for the speed at the measures in Table 6.7. In this analysis the maximum speed between measures has been assumed as the input speed. There is a certain degree of explanation for the speed reduction effect of the measures, however not all drivers follow the trends established in those relationships. For instance, the highest R^2 values refer to the cushions and the second chicane, whereas the lowest values apply to the hump, the table and the first chicane. Hence, this suggests an effect of the input speed upon the effectiveness of the measures in most of the cases. Furthermore, the observation of speed profile plots for the highest entry speed ranges suggests that the effectiveness of the measures in terms of the speed reduction proportion, decreases with high speeds.

Table 6.9 compiles factors affecting maximum and minimum speeds as described by various authors.

Table 6.9: Factors affecting maximum and minimum speeds

Author	Maximum speeds	Minimum speeds
Mak (1986)	not a function of the undulation height; spacing may be a more important factor	---
Taylor and Rutherford (1986)	---	determined more by the physical properties of the device than by approach speeds
Hiddas (1993)	spacing	type and geometry of the device
Lines (1993) and Webster (1993)	spacing (relationship describing mean and 85th%ile between humps as a function of the spacing)	---

Variables have been identified which affect maximum and minimum speeds, assessed through the relationships derived. Although it is quite difficult to identify specific factors influencing speeds, the developed relationships have strengthened the findings and pointed out some evidence in relation to the encountered similarities and differences, so that:

the speed at the device is mainly affected by the type (geometry) of the device itself, while the distance from the previous measure and the maximum speed upstream of the measure play a secondary role; and

maximum speed is affected by a combination of the speed at which the upstream device was crossed and the distance between devices.

Although this is consistent with the factors mentioned in Table 6.9, other variables which may affect speeds in conjunction with those in Table 6.9 have also been identified.

6.2 Acceleration and Deceleration Rates

The objective of this section is the analysis of acceleration and deceleration experienced by drivers when crossing traffic calming devices. Usually this means a deceleration and an acceleration manoeuvre in the vicinity of a calming measure. From this analysis it will be possible to verify the following hypotheses:

g) the likely point to attain the maximum speed between measures;

h) the likely point to achieve the minimum speed, initially assumed to be at the measure;

i) the effect if any of the deceleration rate upon the minimum speed and the effect of the acceleration rate upon the maximum speed; and

j) whether the acceleration and deceleration rates are a function of the type of measure.

This current study of the impacts of traffic calming measures on speeds has been developed based on speed-distance relationships, which restricts the application of known acceleration models based on time relationships, as mentioned in Chapter 3 section 3.5. Furthermore, those models were also developed to explain the S shaped curve for speed profiles, which, to a certain extent, are not found in the speed profiles obtained at traffic calmed links since the initial speed is different from zero implying that the vehicle may have overcome the initial acceleration phase which characterises the S shape. However, it is impractical to quantify the exact portion of the beginning of the curve which has been excluded since the road sensors were not placed very close together to produce a detailed initial portion of the profile.

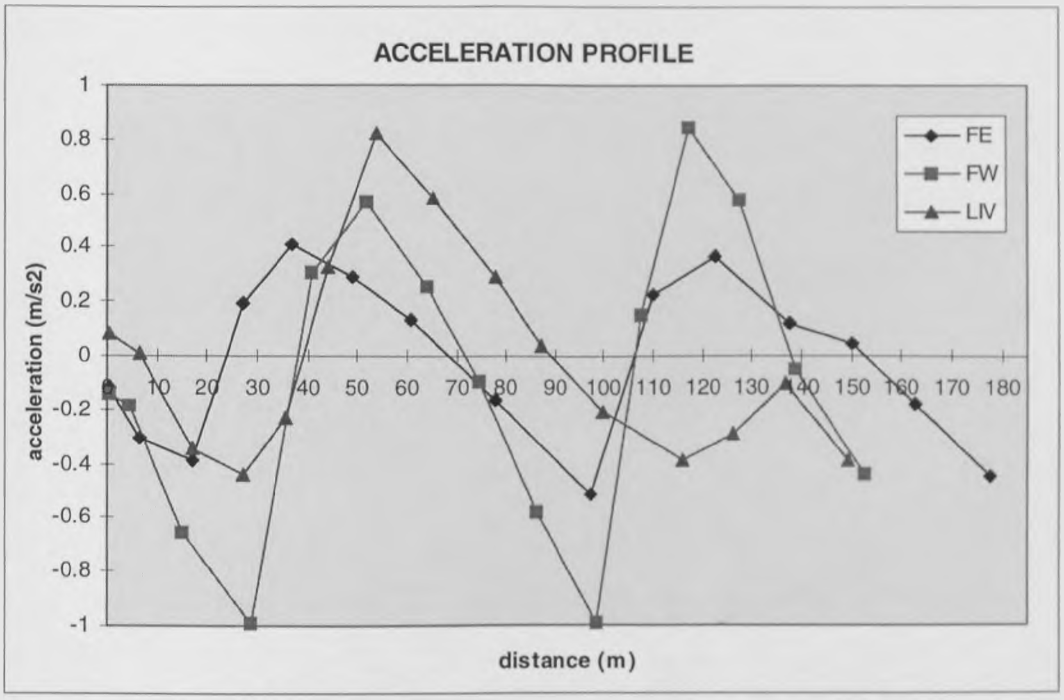
Therefore, the analysis of acceleration and deceleration in the vicinities of traffic calming measures has been conducted based on conventional equations of motion as commented on in the previous chapter.

Consequently, the adoption of Equation 5.2 (presented in the previous chapter) to calculate acceleration, has permitted two different approaches to achieve the acceleration rates in relation to the distance: (a) between each pair of data points which produces the more detailed acceleration profiles (acceleration-distance) shown in the previous chapter, and (b) over small sections of the link comprising more than two data points which provides acceleration patterns by type of measure. The latter approach enabled the calculation of a single acceleration (and deceleration) rate in the vicinity of a traffic calming measure and makes comparison among measures easier.

6.2.1 Average Acceleration Profiles

Average acceleration profile is simply another way of viewing detailed profiles through average values representing the whole sample. This section presents the average acceleration profiles obtained for each site (Foxwood Lane West, Foxwood Lane East and Livingstone Street) and plotted in relation to the midpoint between data points. Acceleration profiles of different sites have been plotted together to facilitate their comparison (Figure 6.1).

The Foxwood Lane East acceleration profile is the smoothest curve and it presents very similar rates for acceleration after individual measures as well as for deceleration before them, reflecting the similar impacts by the same type of measure (speed cushions) on the link. The highest acceleration is found before the cushion on Foxwood Lane West as a result of the large speed variation occurring between the table and the cushion since the table is usually negotiated at lower speeds in comparison to the subsequent cushion. The hump and the table in Foxwood Lane West account for the highest deceleration rates among all measures.



Key: FE = Foxwood Ln East; FW = Foxwood Ln West; LIV = Livingstone St

Figure 6.1: Average acceleration profiles

Livingstone Street presents a high acceleration between the chicanes, which is consistent with the high speeds attained at this point after passing by the first chicane. An atypical feature in this road is related to the deceleration phase occurring after the second chicane. This fact reflects the proximity of a give-way junction as mentioned in the previous chapter.

Mean acceleration and deceleration rates found for these three roads are consistent with the rates reported by Lay (1990). The mean acceleration rate for the UK is 0.5 m/s^2 and decelerations are around 0.8 m/s^2. Australian data indicates mean rates of about 1.0 m/s^2, whereas the figure for the US is 2.0 m/s^2 for cars and 1.5 m/s^2 for trucks (Lay, 1990).

6.2.2 Acceleration/deceleration According to the Type of Measure

This section deals with the calculation of acceleration rates over small sections of the link which comprise more than two data points. In order to undertake this study, firstly it was necessary to identify the sections of road to be considered during acceleration and deceleration phases in the vicinity of each measure at each site. The term 'section of the road' refers to the length of the link taken from the data point at which the acceleration (or deceleration) manoeuvre starts, up to the point at which it ends. Speed profile plots for individual vehicles presented in the previous chapter give an indication of general acceleration/deceleration trends and therefore, these trends have guided the identification and delimitation of the area of acceleration/deceleration manoeuvres.

Accelerations and decelerations, calculated also using Equation 5.2 (from the previous chapter) for individual vehicles at each survey site, are presented in Table 6.10. The road sections have been identified by the data point numbers to which they refer.

Table 6.10: Mean acceleration and deceleration rates by type of measure

FOXWOOD Ln WEST		FOXWOOD Ln EAST		LIVINGSTONE ST.	
SECTION	ACC/DEC (m/s^2)	SECTION	ACC/DEC (m/s^2)	SECTION	ACC/DEC (m/s^2)
3 - 5	-0.824	2 - 4	-0.345	3 - 6	-0.349
5	hump	4	cushion	6	chicane
5 - 8	0.377	4 - 7	0.297	6 - 10	0.502
9 - 11	-0.738	8 - 10	-0.304	10 - 14	-0.286
11	table	10	cushion	14	chicane
11 - 14	0.529	10 - 13	0.237	14 - 16	-0.219
14 - 16	-0.253	14 - 16	-0.315	-	-
16	cushion	16	cushion	-	-

Speed cushions in Foxwood Lane East present similar deceleration and acceleration rates indicating similar impacts. However, the cushion in Foxwood Lane West indicates less deceleration than the remainder of the cushions (in Foxwood Lane East). The table and the hump show a similar but much higher deceleration, while the hump is being higher. The chicanes (Livingstone Street) present similar decelerations and their values are within the range of acceleration/deceleration induced by the cushions (Foxwood Lane East).

The highest acceleration rate is found after the table which is slightly higher than that between the chicanes. This might be a result of the less severe appearance of the cushion (Foxwood Ln West) after having crossed a hump and a table. This behaviour may suggest that the drivers' perception of the severity of a measure affects the speed in addition to a likely desire of recovering time losses while negotiating more severe measures such as humps and tables.

The high acceleration rate for the first chicane in Livingstone Street may result from the relatively long distance to the next chicane. This analysis of acceleration rates by type of measure also points out the atypical deceleration after the second chicane. The cushions show the smallest acceleration rates indicating less speed reduction at the device in comparison to other measures.

6.2.3 The Likely Position to Attain Maximum Speed

Throughout this data analysis, the maximum speed between measures has been considered as the data point at which the maximum average speed was recorded. Nevertheless, it is known that when a vehicle is cruising its acceleration is zero. Therefore, the position at which maximum (cruise) speed is attained can be determined by interpolating the distance values corresponding to where the acceleration profile crosses the x axis while falling. Interpolations from the graphs are presented in Table 6.11 as a proportion of the separation between measures in the direction of travel. The proportions found indicate that maximum speed is attained after the midpoint between measures, usually after travelling between 55 and 64 percent of the distance between measures. This is consistent with the proportion of the distance to attain maximum speed between humps (0.61 ± 0.07) found by Baguley (1981).

Table 6.11: Position to attain maximum speed

SITES	POSITION OF MAXIMUM SPEED (proportion of distance between measures)				
Foxwood Ln West	**Hump**	0.55	**Table**	0.64	**Cushion**
Foxwood Ln East	**Cushion**	0.57	**Cushion**	0.59	**Cushion**
Livingstone Street	**Junction**	0.55	**Chicane**	0.57	**Chicane**

6.2.4 The Likely Point to Achieve Minimum Speeds

The likely point to achieve the minimum speed was initially assumed to be at the measure. Actually average speed calculated at each data point indicates that the minimum speed occurs at the calming measures. Average acceleration profiles also indicate this as the profiles cross the x axis at the location of the measures.

Due to the distance between the previous and next data point to the measure, speed measurements may not have caught the variations in the vicinity of the measure. Consequently, minimum speed may occur before or after the measure midpoint especially when dealing with humps, tables and cushions.

However, not all drivers achieved the minimum speed at the measure. This sort of behaviour is observed in the individual speed profiles and also acceleration profiles. From an examination of the original databases, the percentage of vehicles attaining minimum speeds at a data point not coincident with the measures could be determined. Table 6.12 presents the measures at the three sites and the respective percentage of vehicles attaining minimum speeds one data point before or after the measure. It should be noted that distance between data points has not been taken into account in this quantitative analysis.

In general, percentages are greater after the measures indicating that it is more usual for the deceleration phase to continue after the measure than for the acceleration phase to start before the measure.

Table 6.12: Percentage of vehicles attaining minimum speed one data point before or after the measures

	Foxwood Lane East			Foxwood Lane West			Livingstone St	
	C1	C2	C3	H	T	C	Ch1	Ch2
Before	13	5	5	1	1	13	18	8
After	27	23	-	25	41	-	11	66

The table in Foxwood Lane West presents a peculiar situation with a higher percentage achieving minimum speed after the measure. This is probably as a result of the position of the sensor at the measure, which was actually placed at the beginning of the ramp of the table, since it would be a hazard if placed on top of the measure, which is used as a pedestrian crossing. The high percentage after the second chicane relates to the road design as mentioned in the previous chapter.

Nevertheless, due to the small percentage of this 'unusual' behaviour in addition to a lack of detailed speed profiles in the vicinity of the measures, it seems reasonable to accept that the measure itself is the point at which minimum speeds are normally achieved.

6.2.5 Other Issues on Acceleration/deceleration

The analysis of acceleration has been considered in this study as a tool to provide a better understanding of the impacts of traffic calming measures. The development of an acceleration (and deceleration) profile model has not been covered by the research objectives. However, the speed profile model described in the next chapter has been used to obtain acceleration profiles as reported later in Chapter 7.

In this specific situation of crossing over calming measures, vehicles do not attain a standstill position, and therefore in the deceleration phase they travel from an initial speed v_i to a final speed v_f, where $v_f > 0$. Conversely, the acceleration phase starts at an initial speed $v_i > 0$. As a result, drivers tend to slow down and to speed up in similar proportions, that is the initial (maximum) and final (minimum) speed differential is almost the same for all drivers. The correlation found between V_{maxU} and V_{min} (in section 6.1.4) supports this equivalence of speed differentials. Possibly, if vehicles had come to a standstill position at the measures, similar proportions in speed reduction would not have occurred as the initial speed varies greatly. However, a unique relationship would be unlikely to explain the large variability in acceleration data resulting from drivers' own driving style as shown in the previous chapter (section 5.4.1). Akcelik and Biggs (1987) also reported a large variation in the acceleration data collected.

Attempts to establish linear relationships between entry speed and acceleration have proved not very satisfactory in terms of the correlation coefficients (that for Foxwood Lane East was lower than 10%, the remainder of sites were around 35%) and the residual analysis showed nonconstant variance of the error term for Livingstone Street data, which means the variability about the regression line is greater for larger values of x (entry speed). Although it is possible to resolve such residual problems e.g. by data transformation, the whole process would have become time-consuming and would have resulted in impractical relationships.

Lay (1990) noted that when acceleration/deceleration are assumed to be linearly related to speed more complicated equations result, as follows:

Accelerating	**Braking**
$a = a_0\left(1 - \frac{v}{v_m}\right)$	$a = -a_0\frac{v}{v_m}$
$\frac{v}{v_m} = 1 - \exp\left(-a_0\frac{t}{v_m}\right)$	$\frac{v}{v_m} = \exp\left(-a_0\frac{t}{v_m}\right)$
$\frac{xa_0}{v_m^2} = \frac{a_0 t}{v_m} - 1 + \exp\left(-a_0\frac{t}{v_m}\right)$	$\frac{xa_0}{v_m^2} = 1 - \exp\left(-a_0\frac{t}{v_m}\right)$

where: a, v, and x are acceleration, speed and distance travelled, v_m is the speed before braking and a_0 is the maximum acceleration.

6.2.6 Discussion

The likely point to attain the maximum speed between measures has been determined for each spacing between two consecutive measures through the interpolation of distance values in the average acceleration profile graphs. The position at which maximum speed is attained lies between 55 and 64% of the separation between measures in the direction of travel.

It has been accepted that the measure itself is the point at which minimum speeds are normally achieved which is consistent with the trends at the calibration sites, although a small percentage of drivers achieved minimum speeds at one data point before or after the measures.

The effect of the deceleration rate upon the minimum speed and the effect of the acceleration rate upon the maximum speed were not established since such relationships proved not very satisfactory. Even though this comprehensive analysis has not been undertaken, during its process it has generated a more objective approach through the calculation of acceleration rates which has provided detailed acceleration profiles (on average and for individual vehicles) and specific acceleration and deceleration rates according to the type of measure, which provide a further way of comparing their effectiveness and impact.

The analysis of acceleration rates by type of measure has shown different rates according to the type of measure. It seems that the distance to the next measure and the type of the downstream measure also have an influence on the acceleration rates (e.g. the table and the chicane present similar acceleration rates). Another explanation of this fact relates to the lower speeds when crossing the table consequently requiring a high acceleration rate to attain the desired cruise (maximum) speed.

6.3 Travel Time Assessment

One criticism of the implementation of traffic calming schemes relates to the delays imposed on traffic by the speed reducing devices. This has been a great concern to certain services, such as ambulances, fire engines and to some extent to public transport. This section introduces a brief assessment of the observed travel time in the links covered by this study. From this assessment it is expected to investigate the following issues:

k) whether travel time in calmed links may be determined by the entry speed; and

l) the likely delay (increase in travel time) according to the type of measure.

Travel times have been analysed through the total travel time on the surveyed link as well as by type of measure. The analysis of total travel time has been restricted to the comparison of travel times among survey sites and the study of the relationships between the entry speed and the total travel time.

6.3.1 Total Travel Time

The recorded passing time of the first axle of each vehicle over sensor number 16 (the last sensor in the link) subtracted from the passing time of the first axle over sensor number 1, has determined the total travel time for individual vehicles to cross the survey links. Total travel time obtained for individual vehicles is shown in the histograms in Figures 6.2, 6.3 and 6.4, for each calibration site. The range of travel times is from 11 to 39 seconds, when all sites are considered, but only a small percentage of vehicles takes longer than 31 seconds to cross Foxwood Lane East and Foxwood Lane West links, as can be seen in the histograms. The range of travel times in Livingstone Street are smaller and the two upper classes present very low frequency.

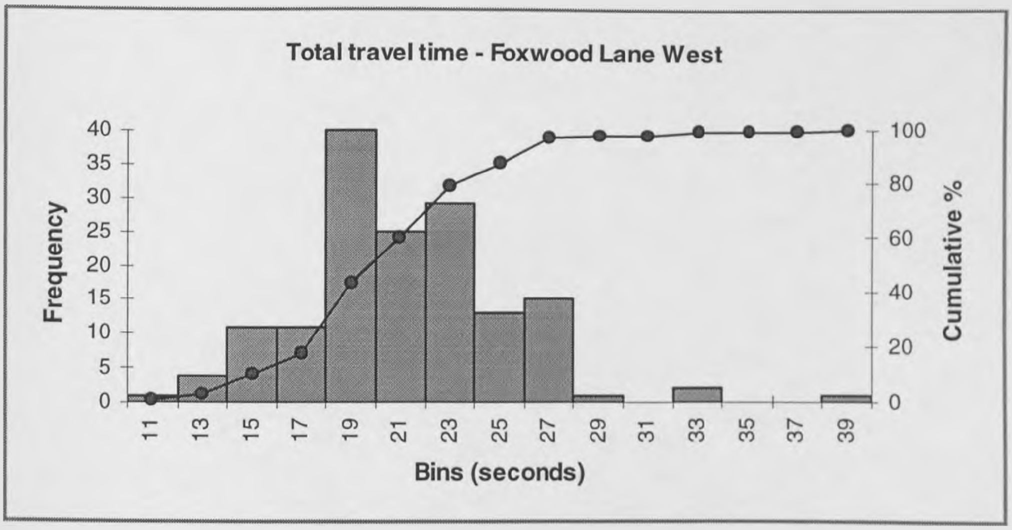


Figure 6.2: Total travel time - Foxwood Lane West

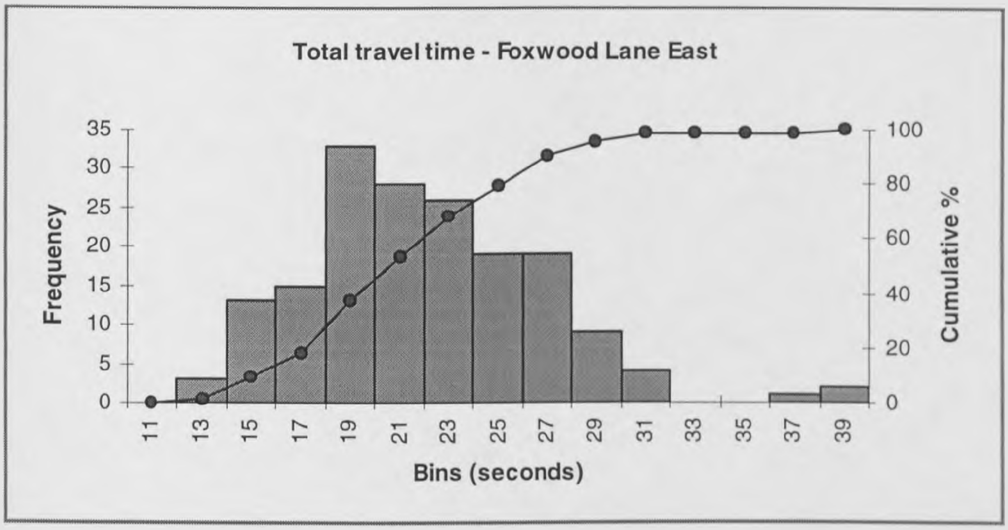


Figure 6.3: Total travel time - Foxwood Lane East

Figure 6.4: Total travel time - Livingstone Street

Table 6.13 summarises the descriptive statistics of total travel times. Livingstone Street presents the lowest variance which suggests a more uniform behaviour among drivers. Foxwood Lane West and East show similar values for the upper and lower percentile, but Foxwood Lane West has a lower variance.

Table 6.13: Descriptive statistics for total travel time

Descriptive Statistics	Foxwood Lane West	Foxwood Lane East	Livingstone Street
Mean	21.07	22.04	19.91
Variance	16.56	22.20	10.58
Standard deviation	4.07	4.71	3.25
Standard error	0.33	0.36	0.24
Minimum	11.27	12.57	13.25
25th Percentile	18.63	18.76	17.61
Median	20.90	21.60	19.41
75th Percentile	23.48	24.90	22.03
Maximum	38.07	39.21	31.80
95% C I Minimum	20.42	21.33	19.43
Maximum	21.72	22.75	20.39

However, as the length of the links varies, this variable should be taken into account in the comparison of travel time. To enable inter-route comparisons, travel times have been expressed in terms of slowness (seconds/km) as defined by Hewitt et al (1974); this is often called 'rate of motion'. The inverse average crossing speed (space mean speed) of each site also enables inter-route comparisons.

Table 6.14 presents the average values of travel times, slowness and crossing speeds calculated for the three links, therefore providing a parameter to compare delays. Among the sites, the Foxwood Lane East scheme exhibits the smallest slowness and therefore the highest average crossing speed. Nevertheless, it has to be borne in mind that even having a common parameter for comparison, this takes into account the whole link rather than individual measures.

Table 6.14: Average travel time, slowness and average crossing speed

Sites	Average travel time (seconds)	Length (metres)	Mean slowness (sec/km)	Average crossing speed (km/h)
Foxwood Ln West	21.07	159.4	132.18	27.23
Foxwood Ln East	22.04	185.0	119.13	30.22
Livingstone Street	19.91	154.1	129.20	27.86

The extra travel time imposed in Foxwood Lane West and Livingstone Street can be estimated based on speed measurements conducted by York City Council before the implementation of traffic calming schemes. Spot speeds were collected using a radar gun. The average speed (55.5 km/h) at Foxwood Lane West resulted in a total travel time of 10.34 sec equivalent to a slowness of 64.87 sec/km. Therefore, the implementation of traffic calming schemes has increased travel time by 11.70 sec, approximately 113%. In a similar way, for Livingstone Street using the data available, the median speed (41.0 km/h) produced a total travel time equal to 13.53 sec and a slowness of 87.80 sec/km. The extra travel time is estimated as 6.38 sec, which represents an increase of about 47%. Attention must be drawn to the fact that these values may not provide an accurate representation of before conditions because speeds were spot speeds and may have varied along the links under consideration.

6.3.2 Travel Time as a Function of Entry Speed (V1)

The entry speed seems to be an appropriate indicator of drivers' behaviour as they reveal their driving style through their entry speed. In this connection, regression analyses were conducted between travel time (dependent variable) and the entry speed. Linear relationships were established for each survey site. A summary of the main regression output is provided in Table 6.15.

Standardised residuals were analysed and approximately 95% of the residuals are between the range -2 and +2, as expected. The regression line fit (predicted travel time) is represented in the scatter plot of observed travel time against entry speed (V1) for each survey site in Figures 6.5, 6.6, and 6.7.

Table 6.15: Summary of regression analysis for travel time relationships

Parameters	Foxwood Ln West	Foxwood Ln East	Livingstone St
R^2	0.646	0.574	0.552
F	275.76	229.35	218.75
travel time (tt)=	36.70 - 0.43V1	37.17 - 0.48V1	33.86 - 0.49V1

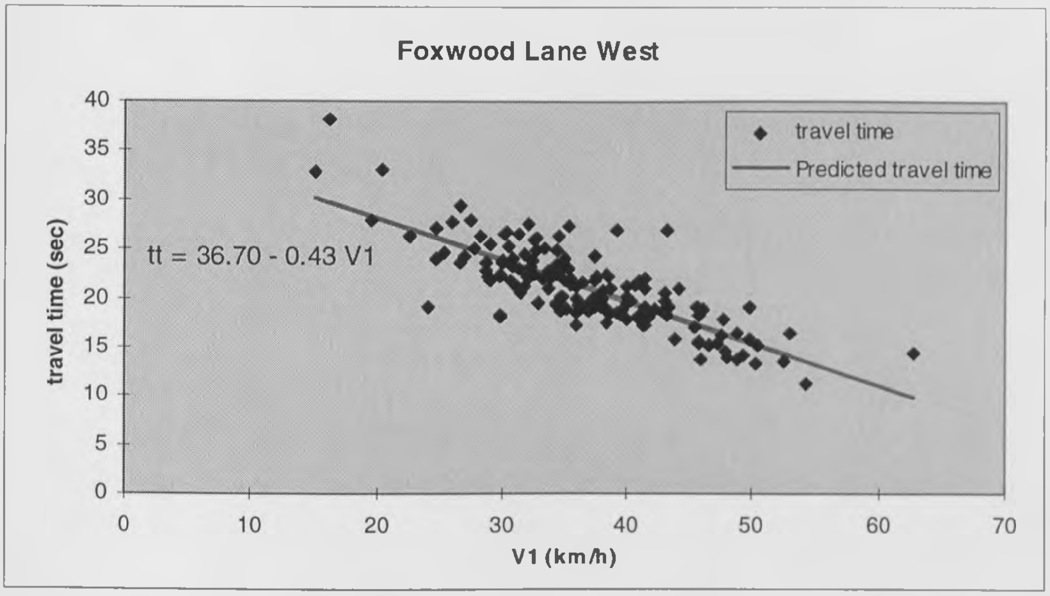


Figure 6.5: Predicted travel time - Foxwood Lane West

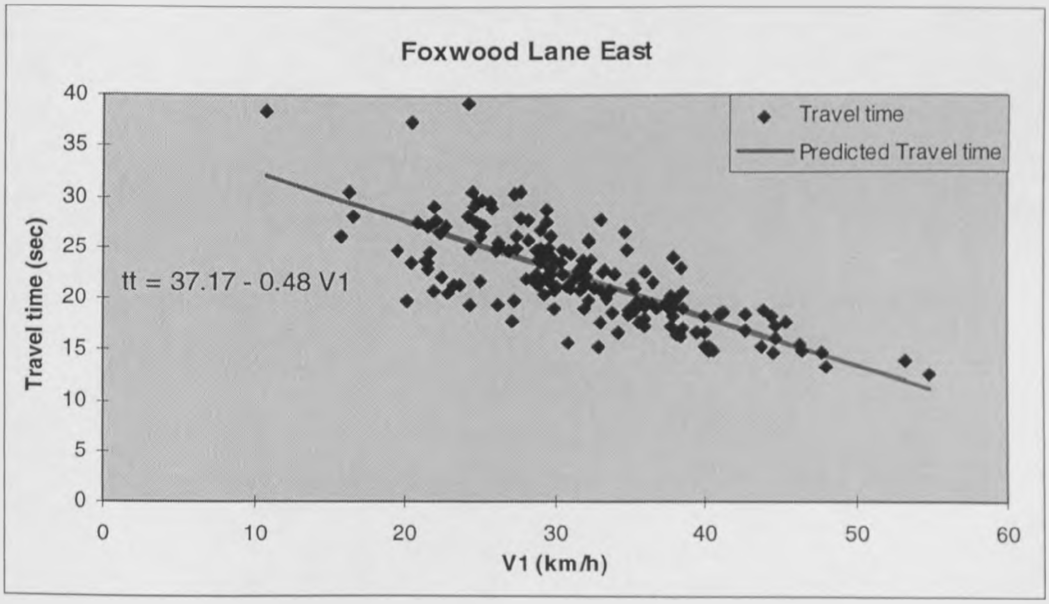


Figure 6.6: Predicted travel time - Foxwood Lane East

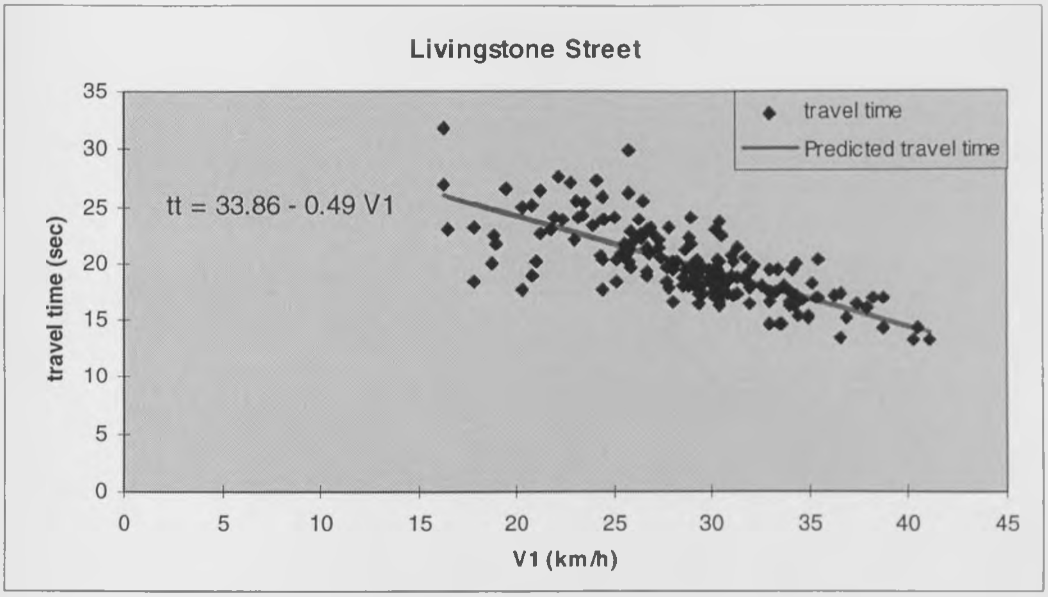


Figure 6.7: Predicted travel time - Livingstone Street

The established relationships provide a reasonable degree of explanation for the total travel time in terms of a linear function of the entry speed. However, it is a simplistic approach, since the effect of the type of measure has not been explicitly considered as an independent variable. It should be stressed that those relationships were developed for specific traffic calming combinations and therefore, their applicability is restricted.

6.3.3 Travel Time by Type of Measure

This approach deals with travel time by sections and includes one measure at a time. Therefore, it aims at establishing the participation of each measure in the total travel time observed in the links. The boundaries of a section correspond to the occurrence of two consecutive maximum speeds so that one section includes the deceleration and acceleration phases surrounding a measure. Hence, Foxwood Lane West and Foxwood Lane East have the same section limits, namely: 1-8, 8-14 and 14-16, and Livingstone Street: 1-11, and 11-16. Nevertheless, the last sections only include one maximum speed data point because the end of the link corresponds to the location of a measure. Travel time values were obtained by subtracting the corresponding passing times of the first axle over the boundary section sensors and are presented in Table 6.16.

Table 6.16: Travel time by type of measure

SITES	Measures	Travel time (sec)	Travel time %	Section length (m)	Slowness (sec/km)	Space mean speed (km/h)
Foxwood Ln West	**Hump**	8.85	42	70.0	126.43	28.47
	Table	8.76	42	62.4	140.38	25.64
	Cushion	3.46	16	27.0	128.15	28.09
Foxwood Ln East	**Cushion**	7.98	36	66.0	120.91	29.77
	Cushion	10.52	48	89.0	118.20	30.46
	Cushion	3.54	16	30.0	118.00	30.51
Livingstone Street	**Chicane**	12.08	60	90.9	132.89	27.09
	Chicane	7.83	40	61.0	128.36	28.01

Values in Table 6.16 enable a few comparisons of travel time by type of measure. The travel time to cross the area of influence of a cushion presents consistent results (similar space mean speeds). The hump and the table show similar travel times and each one accounts for 42% of the total travel time. However if these measures are compared by their corresponding slowness and space mean speed, the table constrains speed to a lower level. Furthermore, if the comparison is made on this basis, the table imposes a greater delay. With regard to the chicanes, it is likely that the space mean speed related to the second one is underestimated because its boundary coincides with the link end, and the downstream junction also accounts for the deceleration after the chicane. With regard to cushions, the slownesses are similar apart from Foxwood Lane West which exhibits a greater value, probably as a result of a short section length.

Differences and similarities among travel time by sections can be easily seen in Figure 6.8 through the plot of cumulative travel times. The graph enables the visualisation of the length of each section as well as the time to cross them. The slopes of each line section also indicate the corresponding speed.

It should be noted that Foxwood Lane East presents a straight line and the slopes by section are equal. A similar situation can be observed in Livingstone Street, but the above mentioned differences between sections should be taken into account. The second section in Foxwood Lane West presents a slightly different slope as a result of the type of measure. The slight differences in slopes (Foxwood Lane West and Livingstone Street) may be noted by the two lines corresponding to each road, crossing each other.

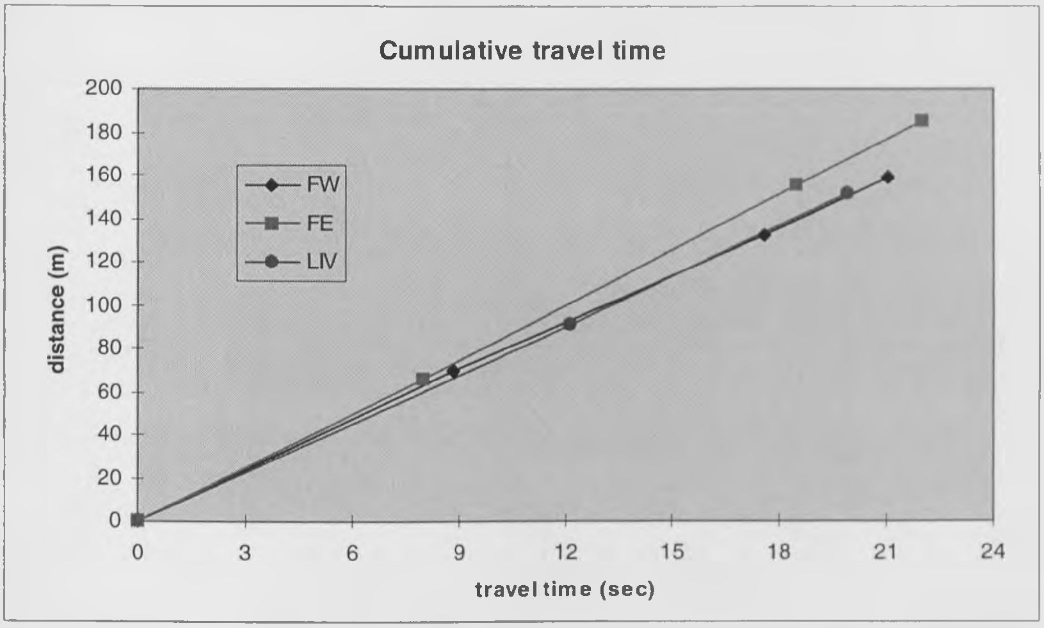


Figure 6.8: Cumulative travel time (by type of measure and by site)

6.3.4 Discussion

The assessment of travel time has been undertaken through two approaches: total travel time and travel time by type of measure. This analysis has also been represented by the slowness in addition to the average crossing speed.

Travel time in calmed links could be determined by the entry speed through the relationships established between entry speed and the total travel time in the surveyed links which have provided a reasonable degree of explanation for the total travel time. The coefficients of the regression equation present similarities within sites. As these relationships were developed for individual links, their applicability is therefore restricted to traffic calming schemes featuring the same combination of measures.

In order to extend the assessment of travel times and to provide a parameter to compare total travel times and delays by type of measure, two dimensions were used (i) space mean speed and (ii) slowness. The comparison of total travel time within sites indicated that the Foxwood Lane West scheme imposes the greatest delay (the highest slowness).

The disaggregated analysis of travel time by the type of measure provides a contribution to the prediction of the required average travel time to negotiate the measures under consideration. Hence, for a given distance, travel time can be estimated based on the space mean speed obtained to travel the deceleration and acceleration lengths surrounding the surveyed measures. Using the space mean speed achieved for each type of measure as a comparison element, the table constrains speeds to a lower level imposing the greatest delay followed by the hump, chicanes and cushions, in this descending order of impact.

6.4 Main Findings

This chapter has introduced the test of hypotheses involving the consistency of the impacts of measures, acceleration and deceleration rates, and travel times. This section summarises the main findings of the data analysis and hypothesis testing which will establish the basis for the next chapter. It considers each hypothesis in turn, as follows:

a) whether the effect of any one measure is consistent wherever it occurs. This was tested using the speeds at the traffic calming measures at the calibration sites; it was found that calming measures of the same design are likely to produce similar impacts on speeds.

b) whether measures in sequence produce an additive effect on speeds. There was no evidence for this; measures of the same type and design have shown similar impacts on speeds wherever they occur in a sequence.

c) whether drivers exhibiting different behaviour (determined through their input speeds) respond in different ways to the measures. This has been analysed by the relationships established between the input speed (actual entry speed) and the speed at the first calming measure. While there is a certain pattern of behaviour, the R^2 values of those relationships 0.42, 0.49 and 0.74, respectively for Livingstone Street, Foxwood Lane West and Foxwood Lane East, indicate that some drivers do not follow that pattern and respond in different ways to the measures.

d) the effect of the input speed upon the effectiveness of the measures. This was analysed by the relationships for the speed at the measures suggesting an effect of the input speed upon the effectiveness of the measures. Nevertheless, not all drivers follow the trends established in those relationships, and hence they do not explain all the variability in drivers' behaviour (five out of eight relationships present R^2 values greater than 62%). Individual speed profile plots for the highest entry speeds suggest that the effectiveness of the measures in terms of the speed reduction effect decreases with high speeds.

e) whether the minimum speed is a function of the type of measure, the input speed and the distance. The speed at the device (minimum speed) is mainly affected by the type (geometry) of the device itself, while the distance from the previous measure, which determines the position of maximum speed, and the maximum speed itself play a secondary role.

f) whether the maximum speed downstream of a measure is a function of the minimum speed at the measure and the distance. The relationships derived suggest that maximum speed is affected by a combination of the speed at which the upstream device is crossed and the distance between measures.

g) the likely point to attain the maximum speed between measures was determined through the interpolation of distance values in the average acceleration profile graphs. The position at which maximum speed is attained lies between 55 and 64% of the separation between measures in the direction of travel.

h) the likely point to achieve minimum speeds was accepted as being at the measure itself. This is consistent with the trends at the calibration sites although a small percentage of drivers achieved minimum speeds one data point before or after the calming measure.

i) the effect of the deceleration rate upon the minimum speed and the effect of the acceleration rate upon the maximum speed. These effects were not established since such relationships proved not very satisfactory.

j) whether the acceleration and deceleration rates are a function of the type of measure. The analysis of acceleration rates by type of measure has shown different rates according to the type of measure. Speed cushions in Foxwood Lane East presented similar accelerations (0.24 to 0.29 m/s^2) and decelerations (around 0.33 m/s^2). The table and the hump presented the highest decelerations (0.74 and 0.82 m/s^2 respectively) and accelerations of 0.53 and 0.34 m/s^2 respectively. The chicanes presented similar deceleration (0.29 to 0.35 m/s^2), whose values are similar to the range observed for cushions, while the acceleration (0.50 m/s^2) is similar to the hump.

k) Travel time in calmed links may be determined by the entry speed. Relationships established between entry speed (V1) and the total travel time in the surveyed links provided a reasonable degree of explanation for the total travel time. However, the applicability of such relationships is restricted to traffic calming schemes featuring similar combinations of measures to those in the surveyed links.

l) the likely delay (increase in travel times) according to the type of measure. This was determined by establishing the participation of each measure in the total travel time observed in the links. The comparison of measures by their slownesses and space mean speeds indicates that the table constrained speeds to a lower level imposing the greatest delay. Cushions showed the highest space mean speeds, hence imposing the least delay.

6.4.1 Final Remarks

The outcome of the analyses has enhanced the understanding of the effects on speed of some traffic calming measures. Two main points should be stressed. Firstly, there is consistency in the impacts of measures on speeds, which has been assessed based on the speed at the device. Secondly, variables which affect maximum and minimum speeds have been identified. The investigation of the hypotheses has given insights into other specific issues which are equally important in the subsequent stage of this research.

These results have suggested the basis for the model development which will be dealt with in the following chapter.

CHAPTER 7

MODEL DEVELOPMENT

The investigation of the hypotheses undertaken in the previous chapter has demonstrated the significance of some of those findings for the next stage of this current research. This stage accomplishes the objectives proposed by this study through the development of an empirical model to predict the effects of certain types of traffic calming measures on speeds of unimpeded vehicles. This chapter presents the basis for the model development, as well as its calibration using data collected at three sites in York, namely Foxwood Lane West, Foxwood Lane East and Livingstone Street. Finally, the recommended model is used to predict acceleration profiles.

7.1 First Modelling Attempts Based on Known Models

The first stages of the modelling process reported here involved tests using the set of data from Foxwood Lane West and Foxwood Lane East. Some of the tests were conducted using a reduced data set extracted from the Foxwood Lane West database, for instance the first 50 observations.

The review of models describing vehicle motion, mainly those describing acceleration through a variety of functional forms (Akcelik et al, 1983), has proved their inadequacy for the type of data involved in this study (speed-distance) as they were developed under time based relationships. While these relationships could be converted to speed-distance, such a transformation would have made them complex to apply.

The first attempt to model the data in the speed profile curves was using the model suggested by Jarvis (1987) and Pitcher (1989a) which relates speed to distance and is of the form: $V^3 = a + bx + cx^2$. This model was used by Pitcher to explain speed profiles (considering the acceleration and deceleration stages separately) of vehicles travelling along links of about 200m.

That relationship was firstly tested using average speed and dividing the link into sections that correspond to the acceleration and deceleration lengths due to calming measures. The addition of the cubic of distance was also tried. The correlation coefficients obtained for such models were very high, around 95%, as a result of the reduction of the data variability. However, correlation coefficients obtained for models dividing the link into sections and based on the whole sample were very poor, less than 25% for Foxwood Lane West and less than 6% for Foxwood Lane East (see Appendix B). When considering speed collected at all data points the results worsened and correlation coefficients of around 50% were achieved when average speed was used.

The shape of the observed speed profile curves suggested the use of polynomial models. Polynomials of the third order assumed values which are false in this specific case as the curve does not account for all peaks and troughs. Although it is advisable to keep the order of the polynomial model as low as possible, another attempt was made to fit a curve which included all 16 data points and this time using a polynomial function of the fifth-order relating speed to distance. This high-order polynomial accounted for the peaks and troughs resulting from the effect of speed reducing devices but it did not account for the type of measure. The correlation coefficient presented reasonable values (> 60% for Foxwood Lane West) when average speed at each data point was used in the regression analysis rather than the whole data set.

The 'Cricket Graphs' software was used for the curve fit of average speeds into polynomials of the fifth-order for both sites. The curve fit option gives the estimated coefficients of the regression equation and the correlation coefficient, which are presented in Appendix B. Despite the high value of the correlation coefficient, the polynomial curve did not appear to relate well to the average speed values.

Finally, using the 'Stanford Graphics' software, individual vehicle profiles showed a well adjusted fit to a polynomial of the 8th degree. However, the results of a regression analysis using SPSS for the average curve were disappointing: the correlation was low; four variables were not in the equation; and the coefficients of the remaining variables were not statistically significant in terms of the t-test.

If a polynomial model were to be adopted, the cubic would probably be adequate as long as it was applied to the acceleration and deceleration portions of the curve separately. It would then result in two modelled curves for each measure comprising the deceleration and acceleration phases. For such segmented models, dealing with one measure at a time, Pitcher's model would also be applicable. However, segmented models are unlikely to produce a continuous smooth curve at their intersections, which usually occur at cruise speed (maximum speed). Moreover, these models would describe the curve but would not account for the type of measure. This may be the main reason for the failure of the two models tested (polynomials and Pitcher's) as overall distance does not describe the position or the type of measure.

Time series analysis was another alternative considered in the modelling process. However, this proved very difficult to apply because the control devices are not uniformly spaced within or between sites (as would normally be the case with time-based sequences), and because the nature of the event (i.e. the control device) at a given point in the sequence differs between sites.

7.2 Establishing the Basis for the Development of an Empirical Model

Since the known models failed to explain the speed profile curves, it was decided to develop a model based on the knowledge acquired from the analysis of the data collected. The main intention was to end up with a simple and practical relationship which describes the effects on speed of different measures and would be easily applicable.

Regression, which is a general statistical tool to develop a relationship between dependent and independent variables, was the technique adopted for the estimation of parameters in the model, thus involving a multiple linear regression model, that is a model linear in the parameters which may or may not be linear in the variables (Gujarati, 1988).

7.2.1 Likely Explanatory Variables

The analysis carried out in the previous chapter has pointed out likely variables affecting speeds along traffic calmed links. It is known that the separation of measures influences the maximum speed attained (Lines, 1993 and Webster, 1993) and in this particular situation, the position of the calming devices is a major factor determining the variations in speeds. In addition the type of measure has been identified as a major factor influencing the speed at the measures (minimum speeds).

The separation of measures and their type contribute to the explanation of maximum and minimum speeds, but the maximum speed variation is usually influenced also by the entry speed (V1). Although the entry speed does not represent the free entry speed, as there may be a previous measure constraining speeds, it has been assumed as such throughout this study. This is a simplification which is imposed on the study by the lack of isolated traffic calming measures, which in turn is a direct result of DoT regulations.

7.2.2 Ways of Describing the Position of a Traffic Calming Measure

The first attempts at modelling speed profiles indicated that overall distance alone does not describe the position of a measure, and that the failure of these models may be associated with this factor. Therefore, the next stage of the model development consisted of devising a way to describe the relative position of the measures in the link.

Initially, to overcome this problem, relative distance was used instead of overall distance. This relative distance approach treats each measure individually and to each one is assigned a relative distance variable so that, for a given measure A, whose distance from the origin is d_a, the relative distance is represented by two variables: D_{A1} (from the origin to the measure) and D_{A2} (from the measure up to the end of the link). Furthermore, these relative distance variables were expressed by a mathematical function to transform the variable distance so that the function would represent an approximation of the actual shape of the curve to be modelled. The function of the inverse of the squared distance $f(x) = 1/(d_a - d)^2$ was applied according to the following logical statement, d being the distance along the link:

$$D_{A1} = \begin{cases} \dfrac{1}{(d_a - d)^2}, & if \quad d_a > d \\ 0 \quad , & else \end{cases} \qquad D_{A2} = \begin{cases} \dfrac{1}{(d - d_a)^2}, & if \quad d < d_a \\ 0 \quad , & else \end{cases}$$

In addition to the function above, two other functions were also tested:

$$f_{(x)} = Ln\left(1 + \frac{1}{|d_a - d|}\right) \quad \text{and} \qquad f_{(x)} = \frac{1}{\sqrt{|d_a - d|}}$$

The former follows the function for the distance suggested by the model of speed change derived by Thomsen and Engel (1992) and the latter relates to the shape of the transition of the curve found at the traffic calming measures which indicates a sharp curve rather than the smooth transition produced by a parabola.

The concept behind the approach of relative distance is fully justifiable. However, because of the nature of these functions, undetermined values were found at the measures, that is the functions tend to infinity at the points which correspond to the position of the measures. Consequently, these transformed functions of distance were subsequently discarded.

Retaining the concept of treating measures individually to describe their location in a link, an objective approach that considers the relative distance between two consecutive measures was devised based on the distance to the next measure (denoted by *dt*) and the distance from the previous measure (denoted by *df*).

To transform overall distance into these two variables is a simple operation of subtracting (in case of *dt*) and adding (in case of *df*) the portion travelled along the link in relation to the distance (spacing) between measures, so that $dt + df = spacing$ between measures. The transformed variables (*dt* and *df*) are represented in Figure 7.1. Values of *dt* equals to zero indicate the position of the calming measures in Figure 7.1.

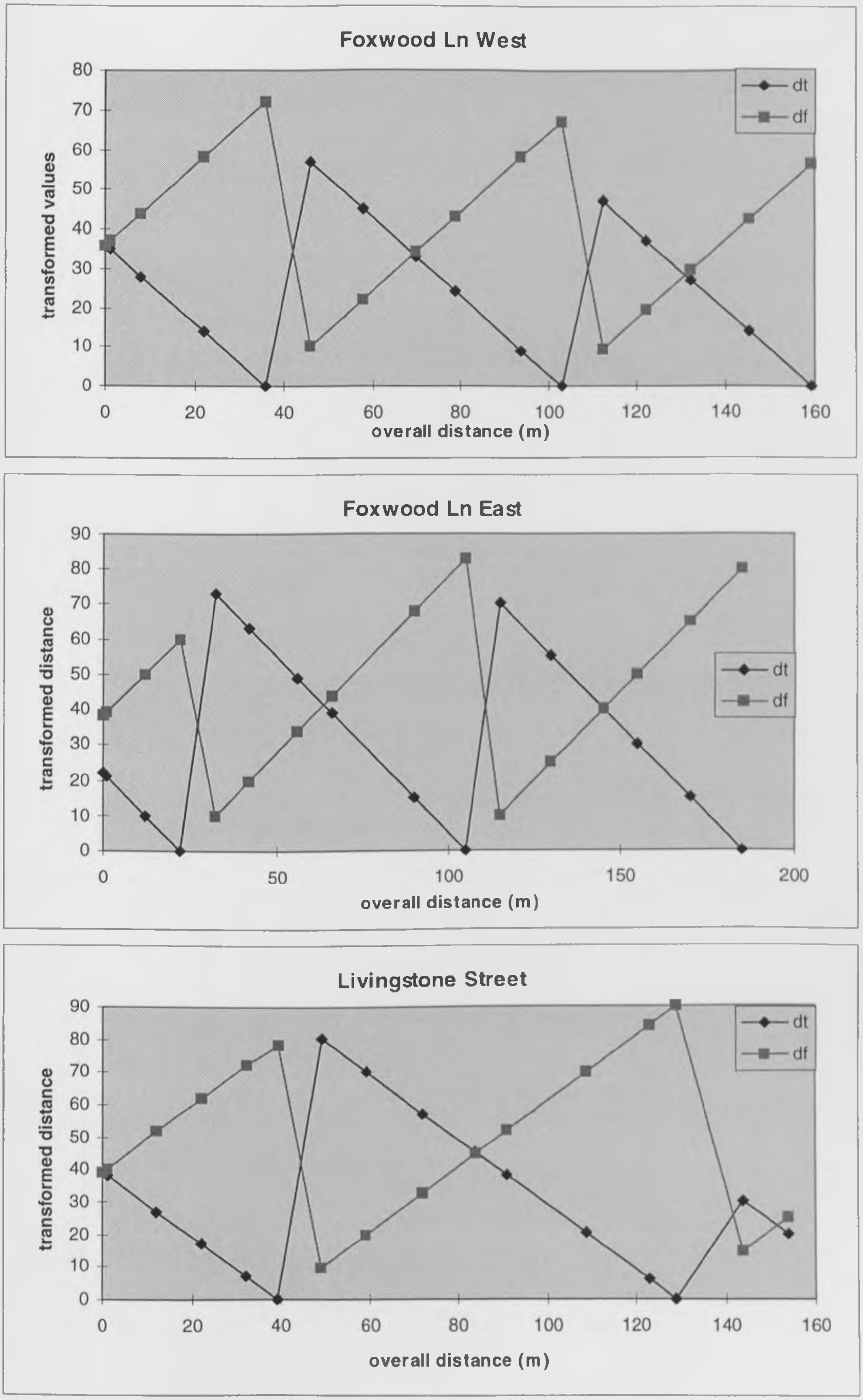


Figure 7.1: Transformed variables - distance to and from - calibration sites

7.2.3 Ways of Describing the Type of a Traffic Calming Measure

The dependent variable, speed, is influenced not only by variables which can be quantified but also by variables which are qualitative in nature such as the type of calming measure. Therefore, in addition to describing the position of a calming measure, it is also necessary to devise a way to describe the type of traffic calming measure since different measures produce different impacts on speeds.

Qualitative variables usually indicate the presence or absence of a quality or an attribute and one method of qualifying such attributes is by constructing artificial variables which takes on values of 1 or 0, 0 indicating the absence of an attribute and 1 indicating the presence of that attribute (Gujarati, 1988). Such variables, called dummy variables, are appropriate to indicate the presence or absence of calming measures.

Different approaches were tested concerning the effect of the dummy variables, namely (a) upstream and downstream variables; (b) area of influence corresponding to the deceleration and acceleration lengths; and (c) local effect.

The upstream and downstream concept relates to the effect of a calming measure (represented by a dummy variable) associated to its position in the link. The effect upstream of a measure affects the stretch of road which precedes the measure. Similarly, the effect downstream of a measure would affect the stretch of road between this measure and the consecutive one. This is illustrated in Figure 7.2 below. Therefore, in the space between two measures there would be two dummy variables acting: the downstream dummy variable for the first measure and the upstream dummy variable for the second measure.

Dummy variable effect:	$\mathbf{H}_{upstream}$	$\mathbf{H}_{downstream}$ $\mathbf{T}_{upstream}$	$\mathbf{T}_{downstream}$
Measure:	**Hump**		**Table**

Figure 7.2: Schematic representation of dummy variable upstream and downstream effect

Assigning the effect of a dummy variable solely to its area of influence, which corresponds to the deceleration and acceleration lengths surrounding a calming measure, requires the determination of the limits of these lengths. The next drawback of this approach relates to the area of transition of effects. This can be treated as an overlapping area where an interaction of effects may occur.

Finally, the local effect considers the effect of a dummy variable restricted to the location where the measure is, that is the effect is solely applied to the data point corresponding to the measure. The results obtained when using these three approaches will be described in the next section.

7.3 Initial Problems - First Lessons

Initially the process of model development involved only the data set of Foxwood Lane West. This site was chosen because there are three different types of measure in this link, which would have made the task more similar to the calibration stage. Subsequently, the tests were extended to Foxwood Lane East and Livingstone Street individually and finally to all sites grouped into one single database matrix.

The starting point, after discarding polynomial models as mentioned previously, involved the use of transformed variables of distance using mathematical functions in addition to dummy variables for the three measures (hump, table and cushion). The use of dummy variables categorised as downstream and upstream variables did not produce satisfactory results as there was an overlapping effect, as shown in Figure 7.2, causing one of the two dummy variables to be excluded from the regression equation, therefore indicating that only one variable would suffice. Despite the problems of undetermined values with these mathematical functions (see section 7.2.4), this model formulation was positive to the extent that it has pointed out problems to be corrected in the next stages: the definition of the influence of a dummy variable and the choice of more appropriate variables to describe the position of the measures. Some of these models are presented in the summary tables in Appendix B.

In the following stage the variables distance to the next measure (*dt*) and distance from the previous measure (*df*) were incorporated into the model. At this stage the parameters which represent the area of influence of a dummy variable corresponding to the deceleration and acceleration lengths were tested. A discontinuity was found in the predicted speed profiles at the point at which the transition of effects occurred. This problem was treated by introducing an interaction effect of the variables, but it did not solve the discontinuity problem. It appeared that a dummy variable is more appropriate to indicate the absence or presence of a qualitative variable, and consequently the effect of a dummy variable should be restricted to the location of the calming measure.

The performance of the tested approaches was assessed firstly by the correlation coefficient, and also by the curve fit. The latter gives an immediate indication of the model's predictive capability and indicates problematic areas and necessary adjustments. The most frequent problem concerned minimum speeds occurring one data point ahead rather than at the position of the measure.

In some of the models tested, the curve fit showed satisfactory results for individual sites. Nevertheless, overall results obtained when grouping all the three data sets (for calibration sites) in order to derive an unique model were disappointing since that model could not provide a suitable curve fit to all three sites, and at least one of the sites showed unrealistic predictions. Furthermore, the correlation coefficients of the models based on individual sites presented higher values than did overall models considering the same variables.

7.4 Model Development

The experience acquired from the initial modelling attempts was fundamental to determine the basis for building the model. Consequently, it was necessary to devise a relationship which would be able to resolve the problems detected. In this connection, the laborious process of testing the ways of describing the position and the type of the traffic calming measures has shed some light on the specification of the model as described below.

7.4.1 Variables in the Model

'A model can never be a completely accurate description of reality; to describe reality one may have to develop such a complex model that it will be of little practical use. Some amount of abstraction or simplification is inevitable in any model building. A few key variables that capture the essence of the phenomenon under study should be introduced into the model, while relegating all minor and random influences to the error term' (Gujarati, 1988).

Hence, according to Gujarati's advice, bearing in mind simplicity and practicality, the independent variables considered in the model are as follows:

- **the entry speed** - VI - is the initial speed in the link which was assumed as the speed measured at the first sensor during data collection (noting that this was taken as indicative of free flow speed) (in km/h);
- **distance to** - dt - is the distance to the next measure in the direction of travel (in metres);
- **distance from** - df - is the distance from the previous measure also measured in the direction of travel (in metres);
- **hump** - H - is the dummy variable which indicates the presence of a hump (0 or 1);
- **table** - T - is the dummy variable which indicates the presence of a table (0 or 1);
- **cushion** - C - is the dummy variable which indicates the presence of a speed cushion (0 or 1); and
- **chicane** - Ch - is the dummy variable which indicates the presence of a chicane (0 or 1).

The second and third order of df and dt were also considered in the modelling process. The reason for their inclusion relates to the shape of the observed profile curves which suggests a polynomial function. The adopted function is non-linear in variables (that is, the variables are raised to the second and/or third power) and linear in parameters (that is, the parameters are raised to the first power only). Therefore, the linear regression model applies.

The variable, overall distance, was also considered in the modelling process. Its inclusion improved the R^2 values slightly, nevertheless it caused disturbances to the curve fit, usually transferring the minimum speed to the next data point. Therefore overall distance was not included in the model. Moreover, it was thought that the overall distance might also have been the cause of the inadequate curve fit found in the first attempts of calibrating the model based on the three sites.

7.4.2 Database Matrix

In order to derive an overall model it was necessary to build a matrix combining the database of the calibration sites. The matrix consisted of 7560 lines (speed data) as the total sample size is 504 and each observed vehicle presented 15 speed values (measured from V2 to V16). Table 7.1 reproduces a simplified database matrix combining data from Foxwood Lane West, Foxwood Lane East and Livingstone Street.

The presence of traffic calming measures has been indicated by the corresponding dummy variables (1 if it is present, 0 otherwise) at the data point which coincides with the location of the measures.

A few assumptions based on the analyses conducted in the previous chapter, were established concerning the use of the dummy variables. Firstly, the four speed cushions existing in the three surveyed links were assumed to have the same impact as suggested by the means (section 6.1.1), that is only one dummy variable cushion, C, was taken into account in the regression analysis. Secondly, although the equivalence of chicanes has not been suggested in section 6.1.2, they were also assumed to have the same impact, (a) because the regression parameter signs were not consistent when the impacts were assumed to be different and (b) for the sake of simplification, since one of the validation sites presents two chicanes and their impact is not known. This issue and its implications for the impacts of chicanes on speeds will be discussed further later in this chapter.

Table 7.1: Simplified representation of the database matrix

	Speed	*V1*	*dt*	dt^2	dt^3	*df*	df^2	df^3	*H*	*T*	*C*	*Ch*
Foxwood Ln West N = 153 2295 lines	V2		35.0			37.0			0	0	0	0
	V3		28.0			44.0			0	0	0	0
	V4		14.0			58.0			0	0	0	0
	V5		0			72.0			1	0	0	0
	V6		57.0			10.0			0	0	0	0
	V7		45.0			22.0			0	0	0	0
	V8		33.0			34.0			0	0	0	0
	V9		24.0			43.0			0	0	0	0
	V10		9.0			58.0			0	0	0	0
	V11		0			67.0			0	1	0	0
	V12		47.0			9.4			0	0	0	0
	V13		37.0			19.4			0	0	0	0
	V14		27.0			29.4			0	0	0	0
	V15		14.0			42.4			0	0	0	0
	V16		0			56.4			0	0	1	0
Foxwood Ln East N = 172 2580 lines	V2		21.0			39.0			0	0	0	0
	V3		10.0			50.0			0	0	0	0
	V4		0			60.0			0	0	1	0
	V5		73.0			10.0			0	0	0	0
	V6		63.0			20.0			0	0	0	0
	V7		49.0			34.0			0	0	0	0
	V8		39.0			44.0			0	0	0	0
	V9		15.2			67.8			0	0	0	0
	V10		0			83.0			0	0	1	0
	V11		70.0			10.0			0	0	0	0
	V12		55.0			25.0			0	0	0	0
	V13		40.0			40.0			0	0	0	0
	V14		30.0			50.0			0	0	0	0
	V15		15.0			65.0			0	0	0	0
	V16		0			80.0			0	0	1	0
Livingstone Street N = 179 2685 lines	V2		38.2			40.0			0	0	0	0
	V3		27.2			52.0			0	0	0	0
	V4		17.2			62.0			0	0	0	0
	V5		7.2			72.0			0	0	0	0
	V6		0			78.2			0	0	0	1
	V7		80.2			9.7			0	0	0	0
	V8		70.2			19.7			0	0	0	0
	V9		57.2			32.7			0	0	0	0
	V10		45.2			44.7			0	0	0	0
	V11		38.2			51.7			0	0	0	0
	V12		20.2			69.7			0	0	0	0
	V13		6.2			83.7			0	0	0	0
	V14		0			89.9			0	0	0	1
	V15		30.0			15.0			0	0	0	0
	V16		20.0			25.0			0	0	0	0

7.4.3 Ordinary Least Squares Regression

Multiple linear regression using the ordinary least squares (OLS) method was applied to estimate the parameters of the function which relates the variables specified in the model. The SPSS statistical package was used to perform the linear regression analysis.

As mentioned previously, in the process of determining an overall relationship for speed it was found that the correlation coefficient between the model and the observed data was lower than the correlation coefficients obtained for the relationships derived for the sites individually. These relatively low correlations have been attributed to the large variation in the collected speed profiles mainly found near the midpoint between the devices and to differences in driver behaviour, as shown in speed profile plots in Chapter 5. The inclusion of the explanatory variable, entry speed, aimed at accounting for a proportion of the variance in driver behaviour. Moreover, the aggregation of speed data collected at different sites (with different traffic calming measures located at different positions along the links) also contributed to the decrease in the correlation coefficients.

The speed variable was investigated as a function of some possible combinations of the partial distance variables, dt, dt^2, dt^3, df, df^2, and df^3. This analysis showed that the addition of higher order partial distance variables only slightly improved the correlation, however it improved the visual model curve fit substantially.

SPSS allows different approaches to be considered in the regression procedures. Two approaches were adopted to look for the best relationship: the ‘enter’ approach that enters all required independent variables at once and the ‘stepwise’ approach that enters the independent variables one by one only if they meet certain statistical criteria. In the latter case a cut-off value for the probability of the F statistic is specified so that the method can determine when F is significant. With the SPSS package, the entry value denoted by PIN is equal to 0.05 and the removal value POUT is 0.10. The ‘enter’ approach was checked against the ‘stepwise’ one which calculates the contribution to the F-ratio for every variable. The order of inclusion is determined by the respective contribution of each variable to the explained variance. The result produced by the enter approach was wholly backed up by the stepwise method.

7.5 The Speed Profile Model

Among the combinations of partial distance variables (the considered combinations are presented in Appendix B), two models produced similar results and also very similar curve fits, including the same number of variables. The criteria adopted in choosing the model relied on the inclusion of all dummy variables in addition to the greatest consistency of the parameter signs, that is in the expected direction, especially those referring to the dummy variables. The model chosen is of the form:

$$Speed = k + \beta_0 V1 + \beta_1 dt + \beta_2 df + \beta_3 dt^2 + \beta_4 df^2 + \beta_5 df^3 + \beta_6 H + \beta_7 T + \beta_8 C + \beta_9 Ch$$

7.5.1 Analysis of the Model Specification

The casewise list of standardised residuals for individual cases has detected 42 outliers beyond 3 standard deviations. For this range it is expected that approximately 0.5% of the observations (two-tailed) will fall outside these limits, which in this case represents approximately 38 outliers. Hence, the number of outliers found is reasonably acceptable. According to Anderson et al (1990) outliers may represent erroneous data; if so the data should be corrected. If they signal a violation of the model assumptions, other models should be considered. But they may simply be unusual values that have occurred by chance. In this case they should be retained.

One of the assumptions of the classical linear regression model is that there is no multicollinearity - exact linear relationship - among the explanatory variables included in the model. The examination of partial correlations indicates no collinearity problem as attested by the correlation matrix presented in Appendix D. It should be noted that *dt* and *df* are highly correlated to their respective powers. Nevertheless, terms like df^2, df^3, are all nonlinear functions of *df,* and hence strictly speaking do not violate the no multicollinearity assumption.

Another important assumption of the classical linear regression model is that the disturbances are homoscedastic; that is they all have the same variance. The residual analysis through the plot of standardised residuals against the dependent variable has indicated the presence of heteroscedasticity. The residual pattern (Figure 7.3) has revealed that the variance of the residuals is proportional to the expected value of the dependent variable, speed. In order to apply remedial measures it was necessary to identify the source of heteroscedasticity.

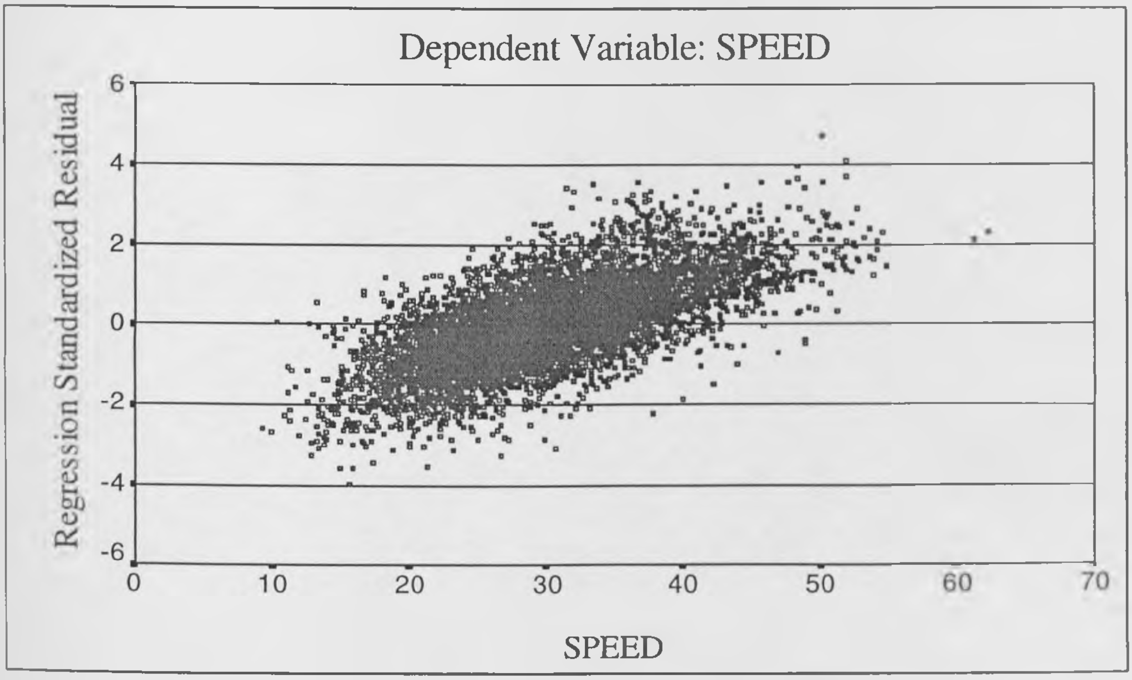


Figure 7.3: Standardised residual vs speed (OLS)

Two tests have been conducted to detect the source: (a) Spearman's rank correlation test as described by Gujarati (1988), and (b) regressing the squared residuals on the variables of the original model and testing the significance of coefficients by means of the t-test. These two tests have yielded the same results indicating that all independent variables except the dummy variable chicane were the source of the problem.

Therefore, it could be concluded that modification of the dependent variable, speed, may reduce the degree of heteroscedasticity. The most straightforward method of correcting heteroscedasticity is by means of weighted least squares.

7.5.2 Weighted Least Squares

To use the method of weighted least squares it was necessary to make a reasonably plausible assumption about the variance and transform the original regression model in such a way that the transformed data would satisfy the assumption of homoscedasticity. Among the several possible assumptions about the pattern of heteroscedasticity considered by Gujarati (1988) are: the disturbances are related to the independent variable; the use of log transformation which is not applicable because some of the independent variable values are zero; and the variance is related to the expected value of the dependent variable. The latter case is the most appropriate assumption to this study since the variance of the residuals is proportional to the expected value of speed, that is $E^2_i = \sigma^2(\hat{Y}_i)$.

The transformation according to the assumption above has been done in two steps: first the usual OLS regression was run disregarding the heteroscedasticity problem to obtain $\hat{Y}_i$, the expected value of speed. Then, using the estimated $\hat{Y}_i$, the original model was transformed by dividing all terms by the square root of the expected value of speed. Although $\hat{Y}_i$ are not exactly the expected value of speed, they are consistent estimators; that is, as the sample size increases indefinitely, they converge to the true expected value. Hence, this transformation is valid if the sample size is reasonably large, which is the case.

Actually, the process of dividing all terms by the weight was not necessary as the WLS function in SPSS, applied to the transformed model, does it automatically when using $\frac{1}{\sqrt{\hat{Y}_i}}$ as the weighted variable as required. Without such transformation, the problem of heteroscedasticity becomes practically insoluble. The WLS regression output has been presented next.

Table 7.2 exhibits the correlation coefficient for the model developed with the WLS regression which has the capability of explaining approximately 55% of the phenomenon 'Speed'. The correlation coefficients for individual sites were approximately 20% greater than the calibrated model, for instance that for Foxwood Lane West was around 67%.

Table 7.2: Regression analysis output for the WLS model

Multiple R	0.740
R square	0.547
Adjusted R square	0.546
Standard Error	1.984

In Table 7.3 is presented the analysis of variance for the regression. The F-statistic value tests the overall significance of the multiple regression. In this test the null hypothesis (H_0) is: all the slope coefficients are simultaneously zero and H_1: not all slope coefficients are simultaneously zero. At the 5 percent level of significance, the critical F value, $F_{0.05}(10,\infty)$ is 1.83, and hence the null hypothesis is rejected.

Table 7.3: Analysis of variance for the regression (WLS)

Source of variance	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F-statistic**
Regression	10	35907.26	3590.73	911.82
Residual	7549	29727.77	3.94	
Total	7559	65635.03		

The next step to check the model specification relates to testing the individual significance of a partial regression coefficient using the t-test. The regression analysis output gives the t-statistic for each estimated parameter which are presented in Table

7.4. In this test the null hypothesis states that, holding the other independent variables constant, a given tested variable has no influence on 'Speed'. If the computed *t* value exceeds the critical *t* value ($t_{0.05,\infty}$= 1.96) for the 95 percent level of significance, the null hypothesis may be rejected. Since the computed *t* values exceeds the critical t value of 1.96, the null hypothesis is rejected and the coefficients are statistically significant, that is, significantly different from zero.

Table 7.4: Parameter estimates of the speed profile model and range of values

Variable	Estimate	Standard Error	t-statistic	Range	
				lower	upper
dt	0.233	0.015	15.159	0	80.2
df	0.779	0.036	21.678	9.4	89.9
dt^2	-0.0012	1.77E-04	-6.983	-	-
df^2	-0.0137	8.43E-04	-16.207	-	-
df^3	8.52E-05	5.82E-06	14.651	-	-
H hump	-4.483	0.420	-10.662	-	-
T table	-6.710	0.414	-16.193	-	-
C cushion	-0.856	0.281	-3.047	-	-
Ch chicane	-2.011	0.369	-5.454	-	-
VI (km/h)	0.622	0.007	84.091	10.78	62.80
(constant)	-8.733	0.575	-15.192	-	-

As a further check on the validity of the regression model developed, the plot of standardised residual against the dependent variable (Figure 7.4) does not exhibit heteroscedasticity and reveals a good residual pattern, randomly distributed, indicating that the model assumptions are satisfied. This scatter diagram can be compared to Figure 7.3, the scatter diagram for the OLS regression. The histogram for the standardised residuals follows a normal distribution with mean equal to zero and standard deviation equal to one (Figure 7.5). Ideally the histogram should have presented all classes within the normal curve boundaries - the central classes do exceed the boundaries whereas some of the mid classes do not touch the normal curve.

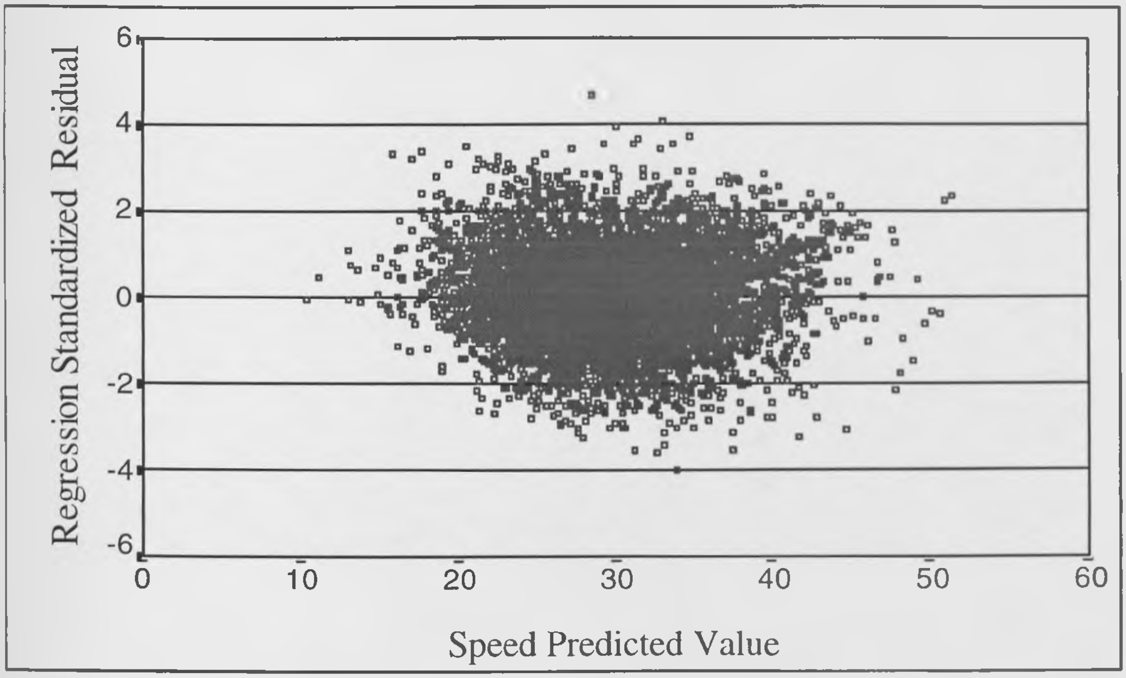


Figure 7.4: Standardised residuals vs speed (WLS regression)

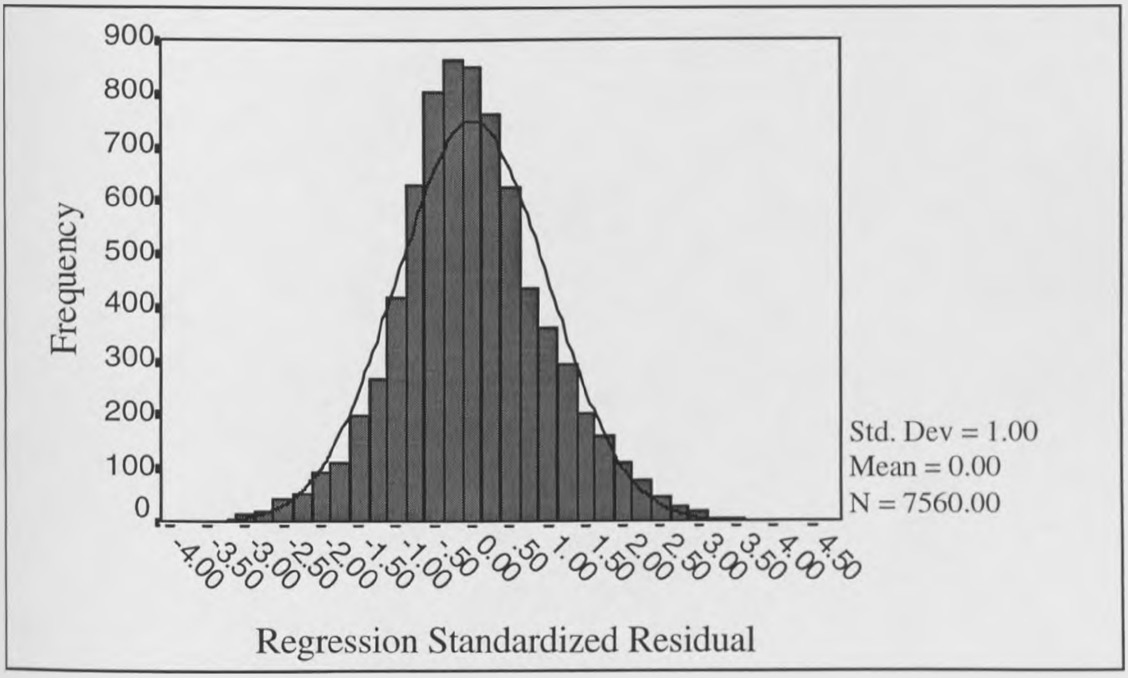


Figure 7.5: Histogram of standardised residuals

7.6 The Model Curve Fit

This section focuses on the graphical representation of the speed profile model. The curve fits have been provided for the calibration sites. The speed values have been obtained by substituting the partial distance values (dt and df) and an arbitrary input speed value into the speed profile model equation. The calculations and graphs were generated in Excel 5.0. To perform these calculations a data matrix containing the partial distance values and their higher orders was built for each site. The formulae written in the spreadsheet combined the parameters of the regression model equation with the data matrix values resulting in 16 speed values predicted for each site in accordance to the desired input speed.

Firstly the speed profile model has been calculated for each calibration site adopting the input speed V1 = 33 km/h which corresponds to 20 mph, the target speed in calmed areas. Hence, 16 speed values have been plotted and shown in Figures 7.6, 7.7 and 7.8 below for Foxwood Lane West, Foxwood Lane East and Livingstone Street, respectively.

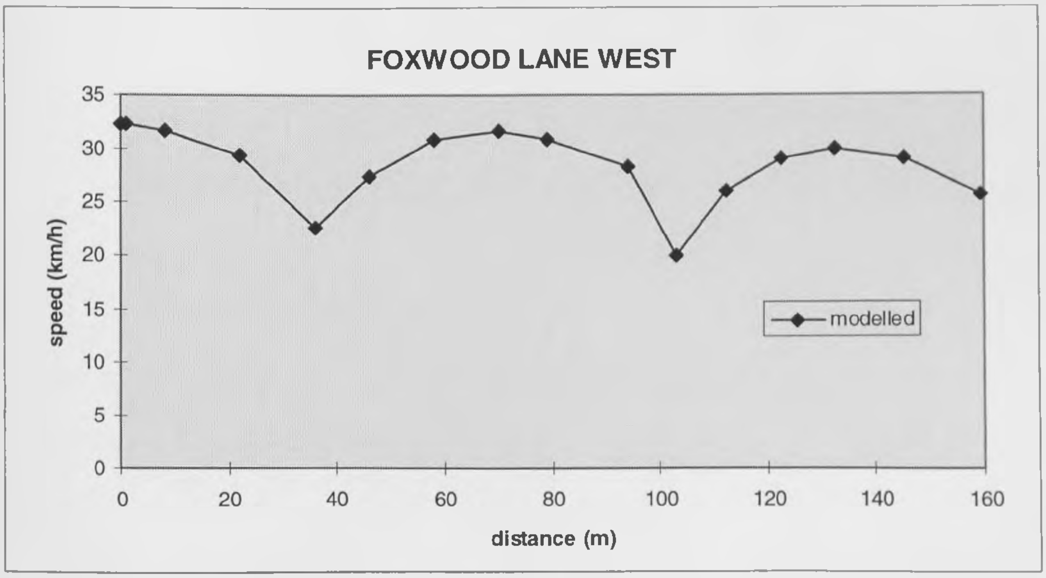


Figure 7.6: Modelled speed profile (V1 = 33 km/h) - Foxwood Lane West

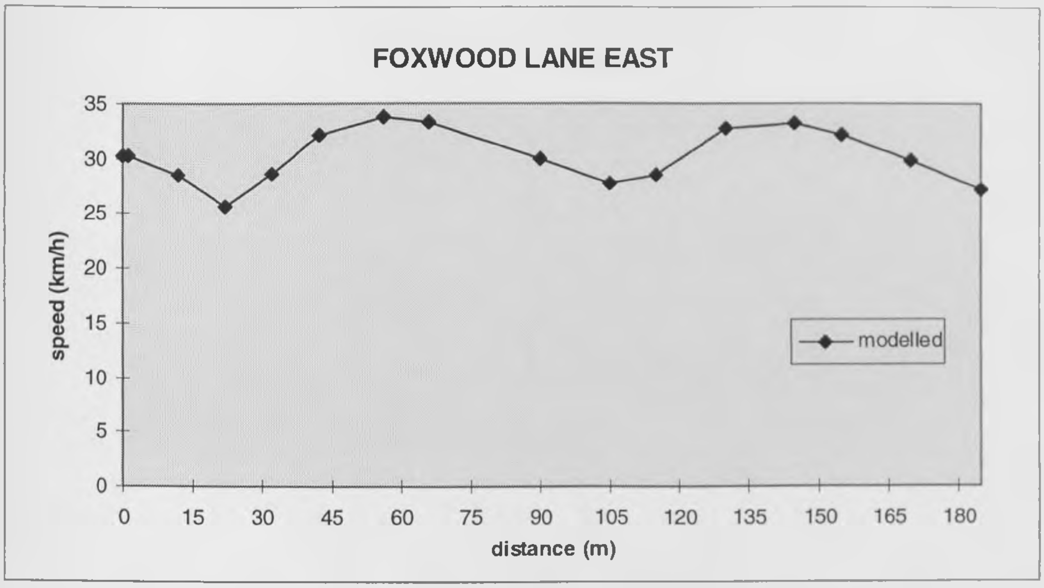


Figure 7.7: Modelled speed profile (V1 = 33 km/h) - Foxwood Lane East

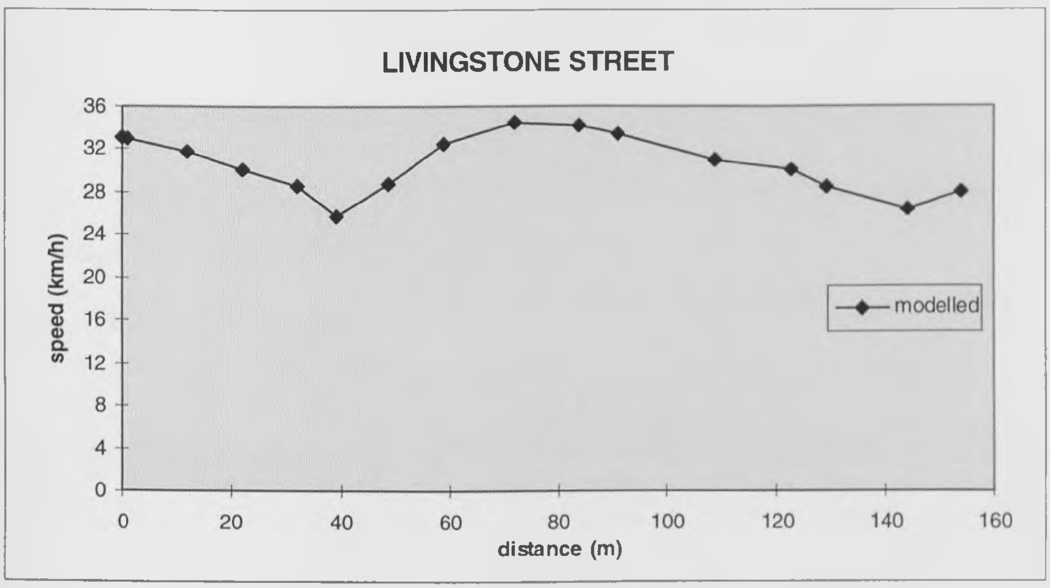


Figure 7.8: Modelled speed profile (V1 = 33 km/h) - Livingstone Street

The modelled speed profile for Foxwood Lane West (Figure 7.6) provides a good representation of the general trends: minimum speeds follow the observed average pattern; the entry speed reproduces the speed value (33 km/h) applied to the equation.

A reasonable prediction has also been achieved for Foxwood Lane East (Figure 7.7), but in this case the predicted entry speed is underestimated. A plausible reason for this low speed may be related to the relatively short distance from the first data point to the first measure (the first data point does not coincide with the actual free flow speed assumed to be attained at that point). The modelled profile indicates more accentuated curves (higher slopes) in the acceleration lengths than the deceleration ones. The deceleration length is longer than the acceleration one. Minimum speeds appear to follow the average pattern. Nevertheless, maximum speeds occur at data point 7 and 13, whereas the average pattern has indicated similar maximum speed values for data points 7-8 and 13-14.

Livingstone Street (Figure 7.8) also presents a reasonable prediction, even for the last portion of the curve where an atypical deceleration is found after the second chicane. Nevertheless, the portion of the profile which contains the maximum speed between the two chicanes (data point 11) appears flatter than the average profile and indicates that the maximum speed occurs at data point 9 instead.

7.7 Goodness of Fit

Among the criteria to judge the quality of a model, Gujarati (1988) lists the goodness of fit measured by the correlation coefficient (R^2) which explains the proportion or percentage of the total variation in the independent variable explained by the explanatory variables. A high R^2 indicates that a model is good, but this criterion alone should not be overemphasised.

In practice, when using data involving several hundred observations, low R^2 values (under 0.6) can be obtained, while finding that the estimated coefficients are statistically significant and signed appropriately. The predictive power relates the comparison of the model prediction with actual data. The R^2 attests to the predictive power of the model within the given sample.

7.7.1 Observed Vs Modelled Profiles

The quality of the model measured by its predictive power has been checked by means of a practical approach which involves the examination of the modelled speed profile curves against the observed ones for a given entry speed range. The predictive power outside the sample is dealt with in the next chapter when the validation data is taken into account. Figures 7.9, 7.10 and 7.11 present the modelled speed profile (thick black line) superimposed on the observed speed profile plots already presented in chapter 5, for actual entry speed ranges containing the input speed V1 = 33 km/h.

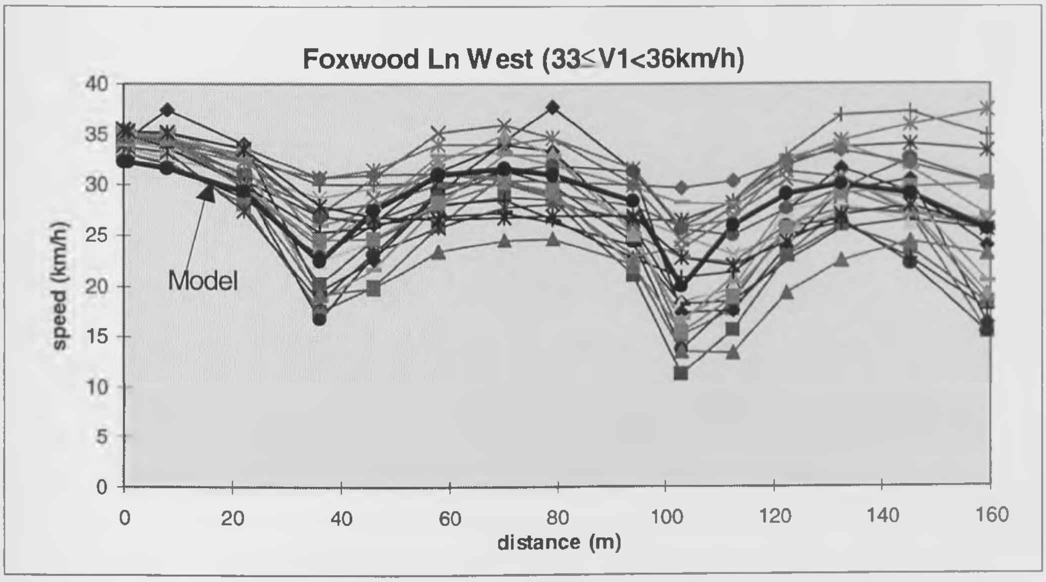


Figure 7.9: Modelled speed profile (V1 =33 km/h) Vs observed speed profiles - Foxwood Lane West

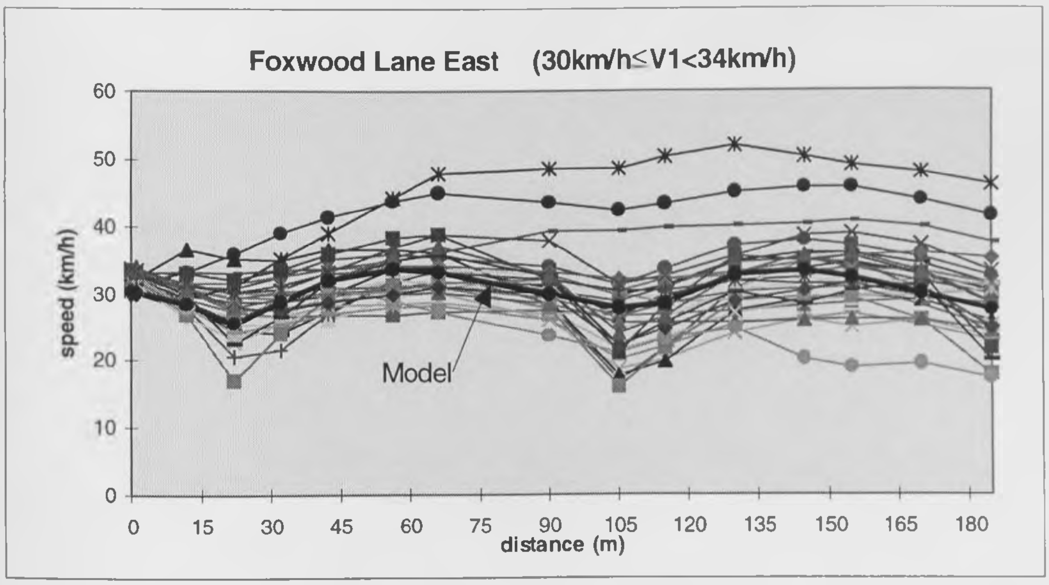


Figure 7.10: Modelled speed profile (V1 =33 km/h) Vs observed speed profiles - Foxwood Lane East

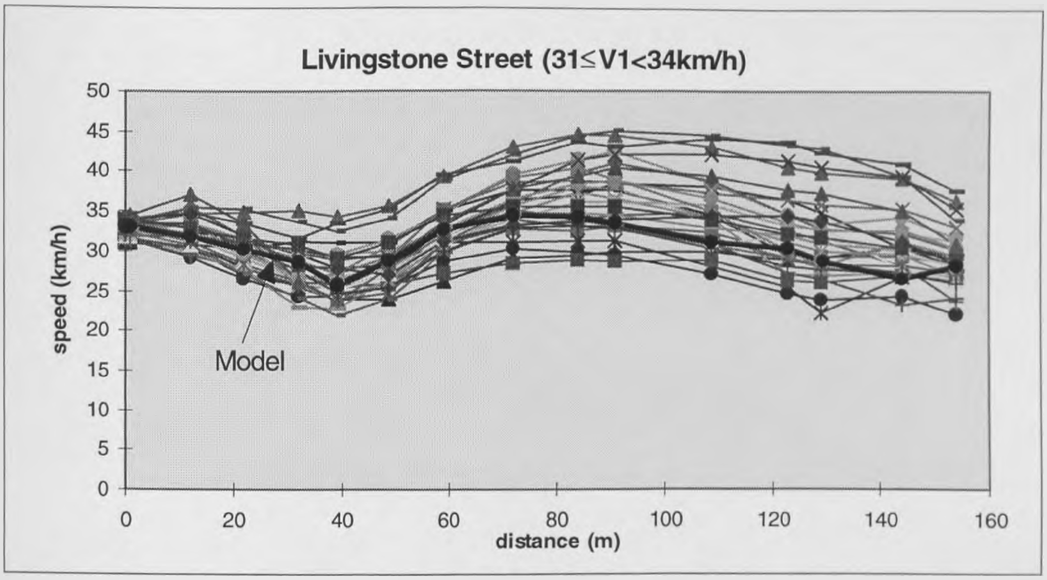


Figure 7.11: Modelled speed profile (V1 =33 km/h) Vs observed speed profiles - Livingstone Street

The modelled speed profile curves appear able to be considered as random observations which may have occurred at the surveyed links due to their similarity to the observed curves. However, the Livingstone Street modelled profile appears to underestimate speeds in the vicinity of the midpoint between chicanes and also at the second chicane.

So far the input speed fed into the model equation has been restricted to the value of 33 km/h. Input speed values equal to the average speed calculated for the first data point (V1) have also been applied to the model equation, in order to compare average speed profiles against modelled speed profiles for which the input speed is equal to the average entry speed. Each site has been associated with a distinct input speed since the average entry speeds vary within the calibration sites. Hence, the input speed for each site is as follows:

Foxwood Lane West	36.61 km/h;
Foxwood Lane East	31.79 km/h; and
Livingstone Street	28.74 km/h.

Figures 7.12, 7.13 and 7.14 depict the average and the modelled speed profile curves. The modelled profile for Foxwood Lane West presents the closest representation to

the average one. Foxwood Lane East underestimates speeds up to the first cushion and also the deceleration lengths in addition to transferring maximum speeds one data point earlier than the average profile.

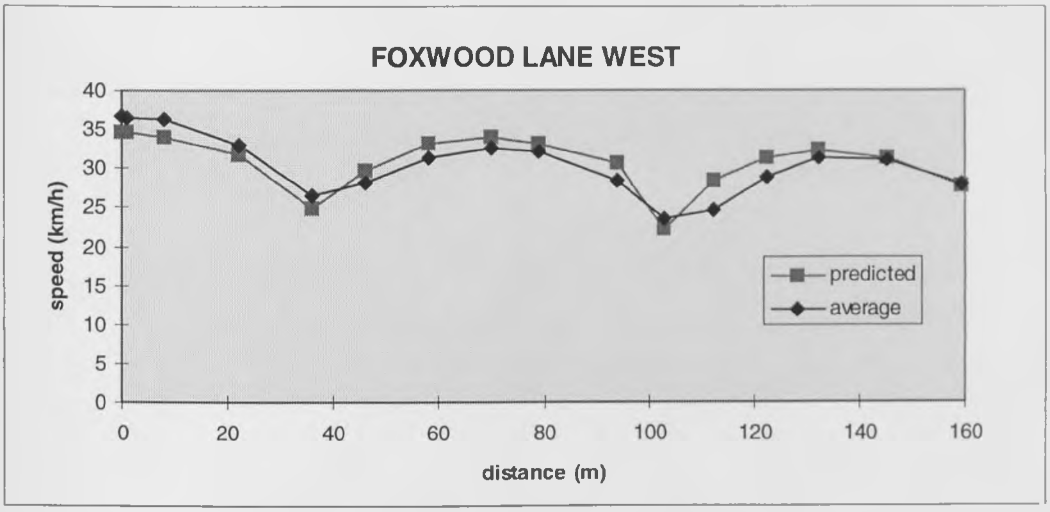


Figure 7.12: Average versus modelled speed profile curve - Foxwood Ln West

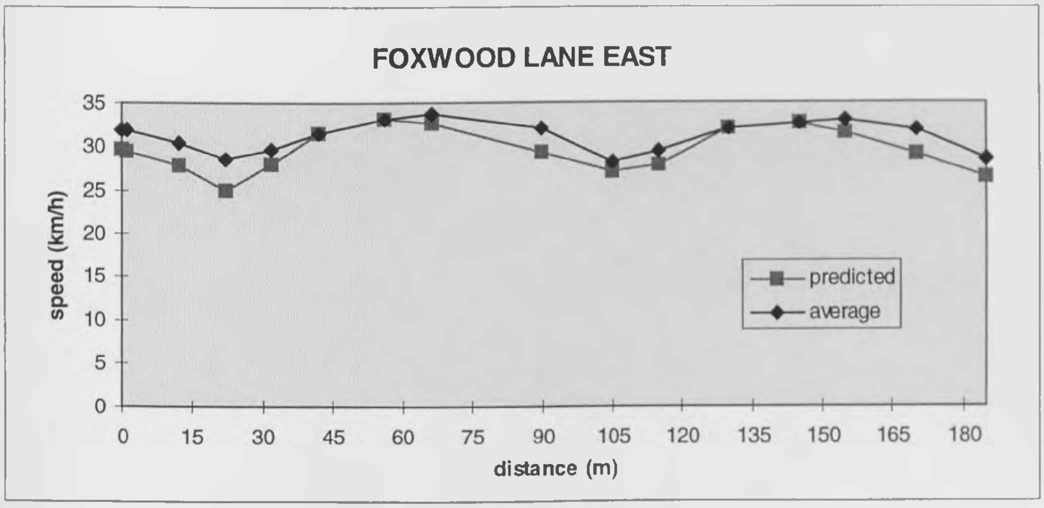


Figure 7.13: Average versus modelled speed profile curve - Foxwood Ln East

The modelled profile for Livingstone Street (Figure 7.14) demonstrates that speeds are being underestimated after the midpoint between chicanes. It appears the profile has been shifted down by a constant value. The last data point presents a discrepancy, indicating opposite behaviour to the average one. Such a discrepancy is not very extraordinary since the behavioural trends at the end of the link are not very consistent, given the effect of the downstream junction.

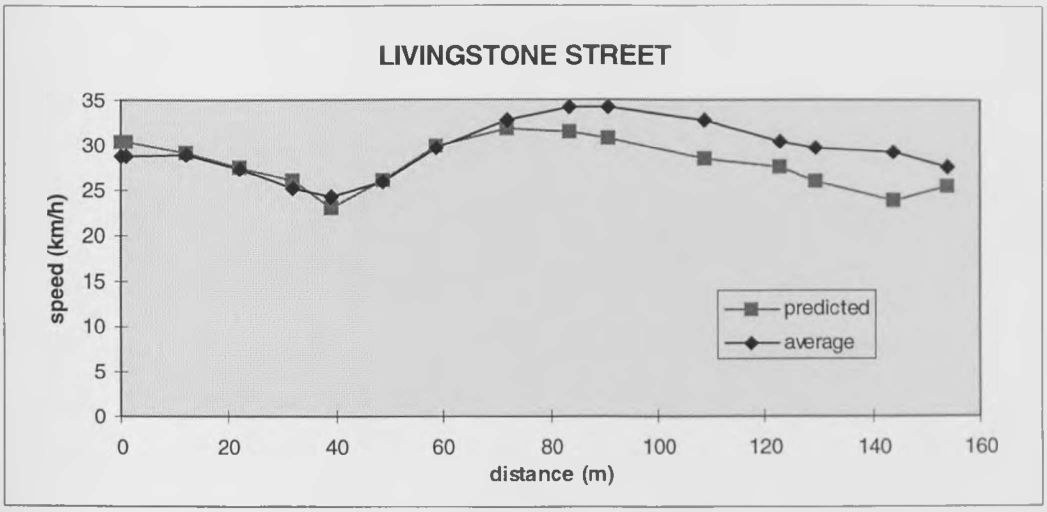


Figure 7.14: Average versus modelled speed profile curve - Livingstone Street

7.7.2 The Model Response to Various Input Speeds

This section examines the model response when different input speeds are taken into account. Hence, the model equation has been used to predict speed profiles for input speeds of 25 and 40 km/h (as well as 33 km/h which corresponds approximately to the midpoint of that speed range).

The examination of the speed values obtained at each site, demonstrates that the speed profile curve shifts up or down within a constant value equal to 62% of the speed differential (the estimated coefficient for the entry speed is 0.62). In other words, having V1 = 33 km/h as the base speed profile curve, for instance, if V'1 = 40 km/h then the new speed profile curve will be shifted up according to a constant value = 0.62 (40 - 33) = 4.34 km/h.

Figure 7.15 depicts the graphical representation of the three speed profile curves plotted for Foxwood Lane West, from which it can be seen that the curves have been shifted up (40 km/h) and down (25 km/h) in relation to the speed profile representative of V1 = 33 km/h. It can also be noted that the input speed of 40 km/h underestimates the entry speed, whereas the input speed of 25 km/h overestimates it.

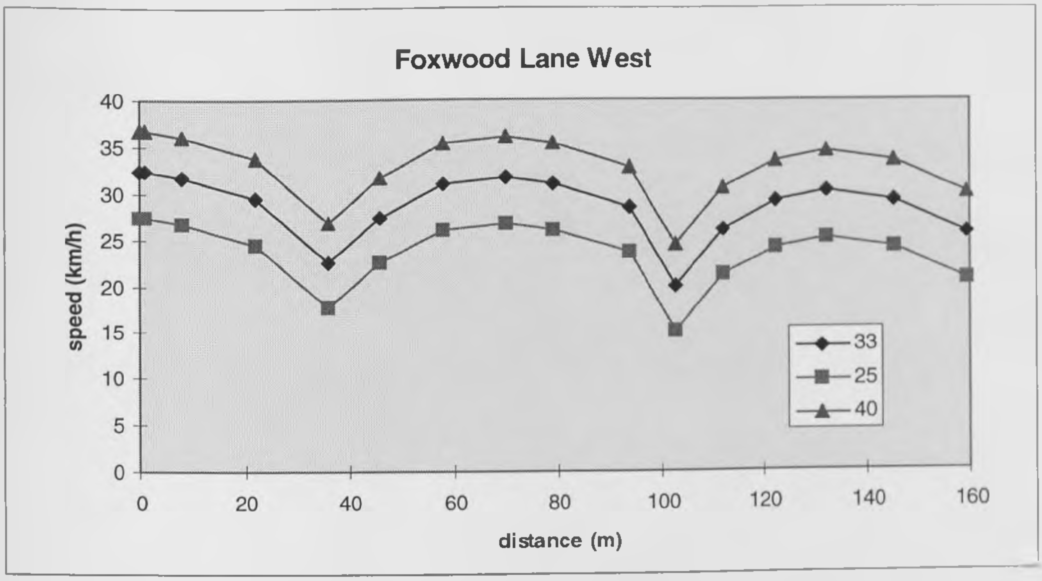


Figure 7.15: Modelled speed profile according to the entry speed - Foxwood Lane West

An input speed of 33 km/h yields the most similar predicted entry speed (V1) apart from Foxwood Lane East, where an input speed of 25 km/h is the best prediction (predicted speed = 25.34 km/h). It seems that for input speeds greater than those which give the optimum prediction for the entry speed, the prediction is underestimated, and overestimated for input speeds less than the optimum prediction.

Some discrepancies have been found in Sections 7.7.1 and 7.7.2 concerning the predictive power of the model within the calibration sample. These discrepancies may generate suspicions about the validity of the model, therefore its predictive power has been further checked based on the residual analysis in the next section.

7.7.3 Sensitivity Analysis

The analysis conducted in this section makes use of statistical procedures, mainly the analysis of residuals. It is, to a certain extent, another verification of the goodness of fit of the model.

This process was developed to enable comparisons between the observed and the predicted speed profile curves in terms of the standardised residuals. The predicted curves have been calculated by feeding the actual entry speed value into the model equation. Hence, for each observed profile there is a corresponding predicted profile. Comparisons have been undertaken between these profiles, therefore allowing the calculation of the standardised residuals using the following expression:

$$\hat{e} = \frac{e_i - \bar{e}_i}{sd(e_i)},$$

where: $\hat{e}$ = predicted standardised residual

e_i = expected - observed speed value (i = data point 1 to 16)

$\bar{e}_i$ = average error

sd = standard deviation

Standardised residuals were obtained from the comparison between predicted and observed speeds resulting in a matrix of standardised residuals of 16 rows (data points) by N columns (N= sample size).

Outliers

The inspection of residuals by rows has indicated the number of outliers for each data point, that is residuals outside the expected range -2, 2 for the 95% confidence level. Table 7.5 shows the number of outliers found for each data point.

Table 7.5: Number of outliers by data points

Site	exp	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
FW	8	1	1	0	0	16	0	0	0	0	4	26	7	1	1	2	10
FE	9	11	10	0	6	0	2	0	0	2	8	2	2	1	0	0	9
LIV	9	9	6	0	0	3	0	1	2	1	0	0	1	0	4	19	5

key: exp = expected number of outliers within the 95% confidence interval

FW = Foxwood Ln West; FE = Foxwood Ln East; LIV = Livingstone St

The incidence of outliers exceeding the expected number, is more frequent at the measures (FW, FE); at the first data point (FE, LIV); and after the second chicane (LIV), as a result of the great variability in drivers' behaviour.

Residual analysis

A further check on the residuals through the scatter diagram of standardised residuals against predicted speed at the location of the measures, reveals that the residuals are randomly distributed and no systematic pattern is found. An even residual distribution is also observed for the entry speed at each survey site.

Absolute Error

The difference between the predicted speed and the observed speed calculated for the first data point gives another indication of the model's predictive capability in terms of the absolute error. This error measured in km/h, points out the speed ranges for which the model yields the least error. In order to establish a comparison parameter, the confidence interval found for the average speed at the first data point has been assumed as the least error expected during prediction.

Speed intervals that produce errors within the expected range specified by the confidence interval, have been determined from the examination of a list of errors sorted by ascending values. Table 7.6 demonstrates the speed range for optimum entry speed prediction which was found through this procedure.

Table 7.6: Input speed intervals for optimum entry speed prediction

Sites	Confidence interval for entry speed (V1)	Optimum prediction speed range
Foxwood Lane West	± 1.23	27.75 - 34.60
Foxwood Lane East	± 1.13	22.76 - 29.40
Livingstone Street	± 0.73	32.90 - 36.90

These speed intervals found are consistent with the analysis of the model response to various input speeds conducted earlier. For instance, this analysis attests that an input speed of 33 km/h does not yield very consistent entry speed for Foxwood Lane East. In fact, this input speed value is outside the range determined according to the confidence interval of the mean entry speed. Therefore, within the specified input speed intervals the model is expected to yield the most similar predicted entry speeds.

7.8 The Use of the Speed Profile Model to Predict Acceleration Profiles

Instead of initiating a complete new approach to develop a relationship for acceleration profiles, it was decided to use the speed profile model as a starting point to reach a relationship or a prediction tool for acceleration at calming measures.

Based on the equation $a = \left(\frac{dv}{dx}\right)v$, the first derivative of speed with respect to displacement (distance) was considered to derive a relationship to describe acceleration profiles. The first constraint related to the variable distance, which has been specified in the model as partial distance and has two different but complementary functions. This approach needs to account for a relationship between *df* and *dt* to transform these variables into one, for instance the spacing between measures so that the derivative can be done with respect to spacing instead. Nevertheless, it would result in an unwieldy expression with little applicability.

Therefore, a simpler approach, also based on the concept underlying the above equation, was used by substituting the term *dv/dx* by the difference quotient $\Delta v/\Delta x$ to represent the rate of change of v with respect to x, so that:

$$a = \left(\frac{\Delta v}{\Delta x}\right)v \qquad (7.1)$$

The difference quotient $\Delta v/\Delta x$ is a good representation of the current situation since the distance between data points is known and since the acceleration rates have been obtained by considering the speed differential in relation to the corresponding distance.

Having the speed profile model as the basis for the acceleration prediction, it is natural that some of the weaknesses of the speed profile model will produce undesired effects (unreasonable predictions) in some situations. Therefore, the acceleration model capability prediction will be tested for the calibration data, bearing in mind its limitations.

The application of Equation 7.1 is straightforward. Once the values of v are known (obtained from the speed profile model equation), the difference quotient $\Delta v/\Delta x$ is easily calculated in any spreadsheet (Excel was again used for this task). Nevertheless, the easiest way to examine it is visually by plotting the predicted acceleration against the average values obtained from the observed data. This procedure allows the comparison of trends.

Similarly to the analysis of the modelled speed profiles, the predicted acceleration profiles based on an input speed of 33 km/h have been superimposed on the acceleration profiles, already presented in chapter 5, according to the entry speed. In addition the modelled profile representative of an input speed equal to the average entry speed has been plotted together with the average acceleration profile to ease comparisons.

Figure 7.16 shows the adequacy of the acceleration prediction for Foxwood Lane West. The fit is generally good. However, the acceleration rates before and after the table (at 103 metres from the origin) appear overestimated. This can also be observed in the average profiles in Figure 7.17.

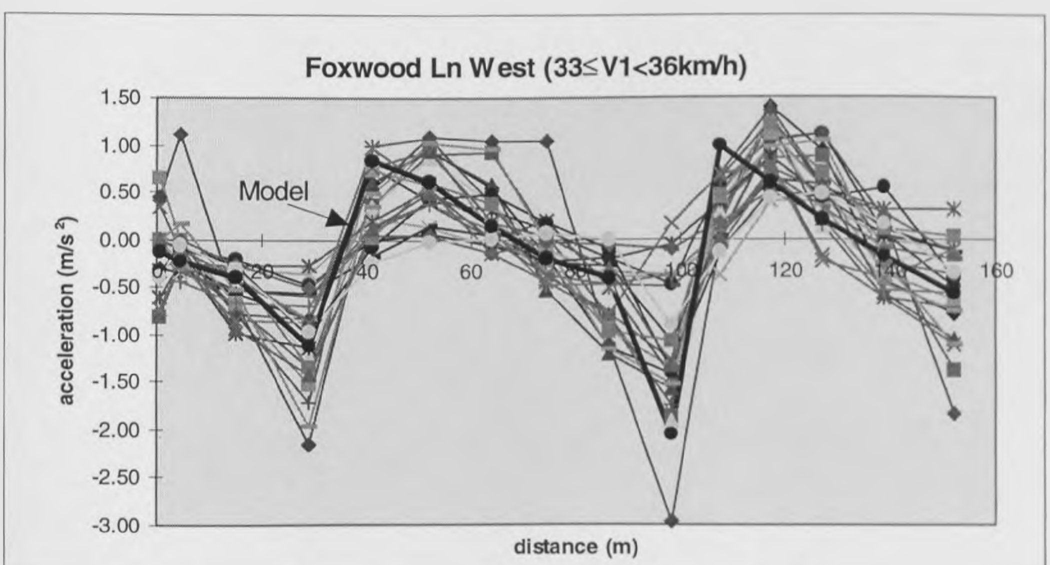


Figure 7.16: Predicted acceleration profile (V1 = 33 km/h) Foxwood Lane West

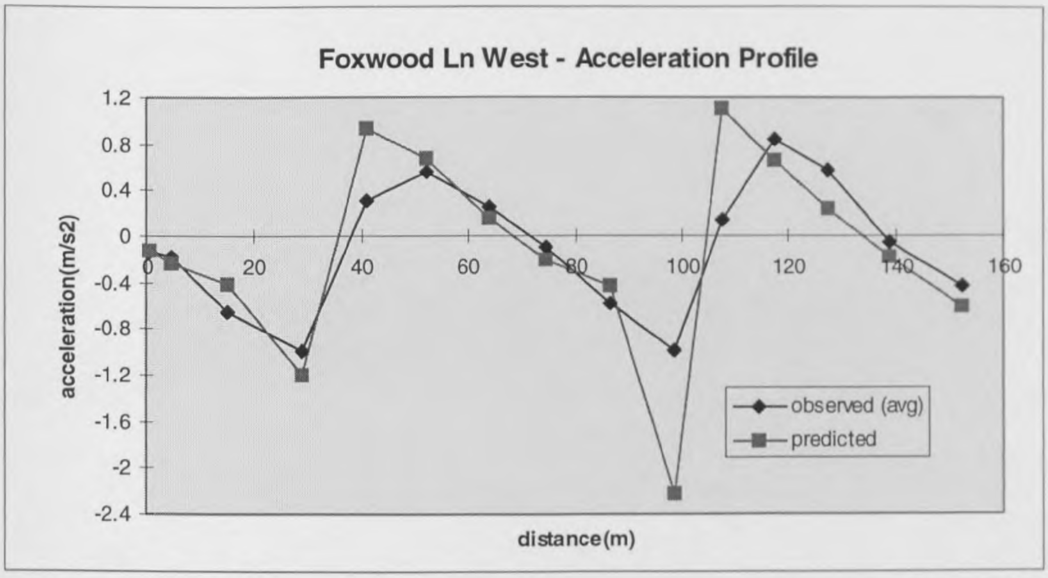


Figure 7.17: Modelled versus average acceleration profile - Foxwood Lane West

Figures 7.18 and 7.19 for Foxwood Lane East highlight two discrepancies: a slight decrease in the deceleration between 80 and 100 m, whereas the observed profiles indicate an increase in deceleration rates; and an anticipation of the point at which maximum speed is attained (between cushions).

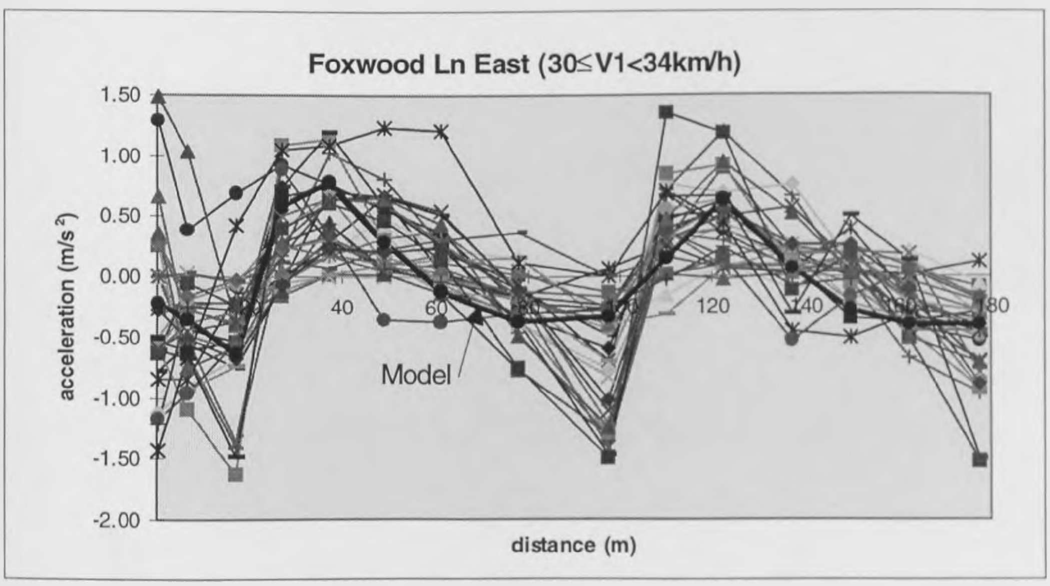


Figure 7.18: Predicted acceleration profile (V1 = 33 km/h) Foxwood Lane East

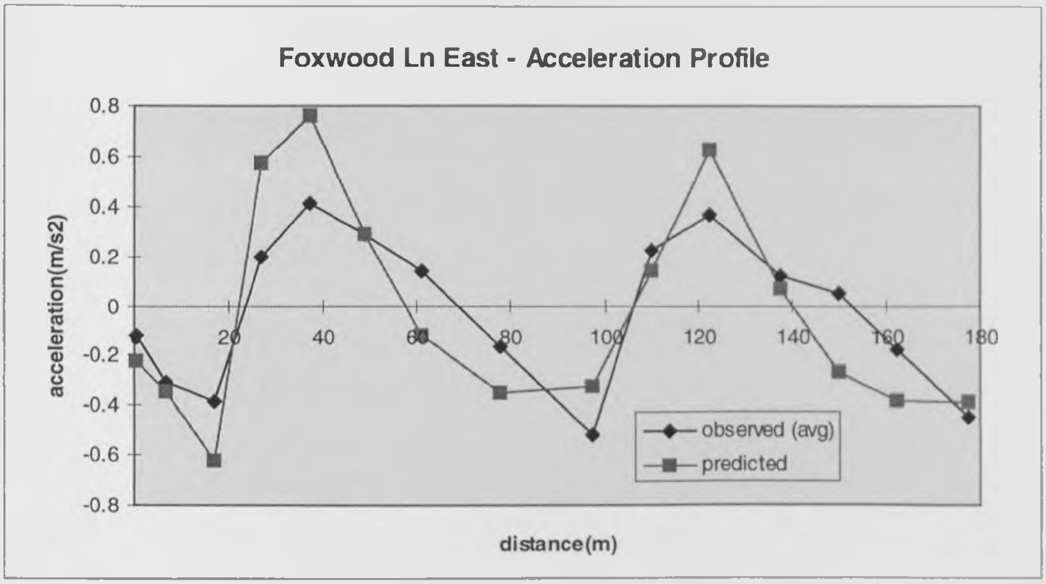


Figure 7.19: Modelled versus average acceleration profile - Foxwood Lane East

The main dissimilarity encountered at Livingstone Street relates to the underestimation of acceleration from midway between chicanes onwards (Figures 7.20 and 7.21). The high deceleration predicted before the first chicane seems not well adjusted to the observed profiles. The prediction in the last portion of the profile may result from the general trend of acceleration after the calming measures occurring at all survey sites.

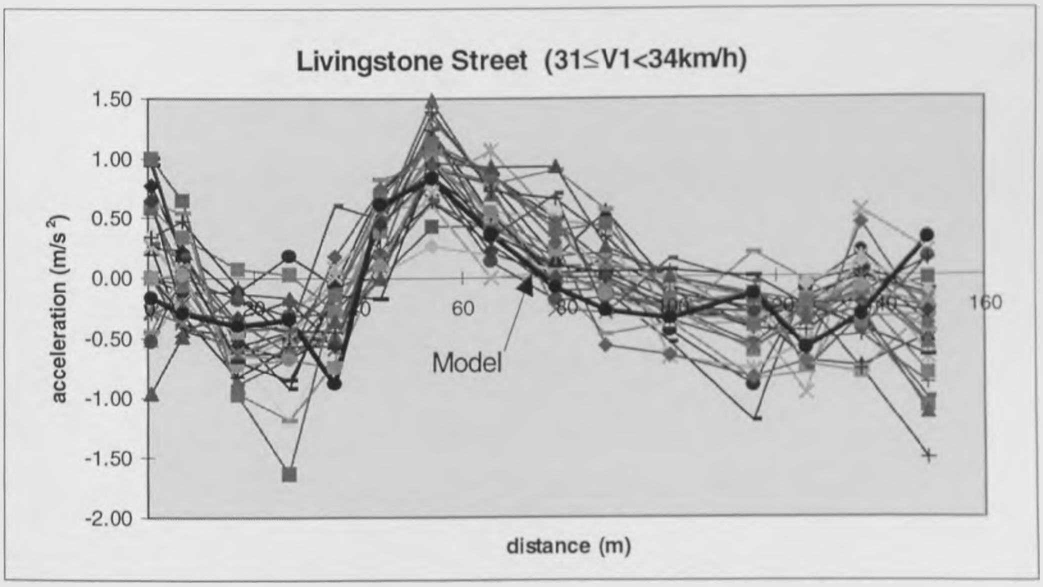


Figure 7.20: Predicted acceleration profile (V1 = 33 km/h) Livingstone Street

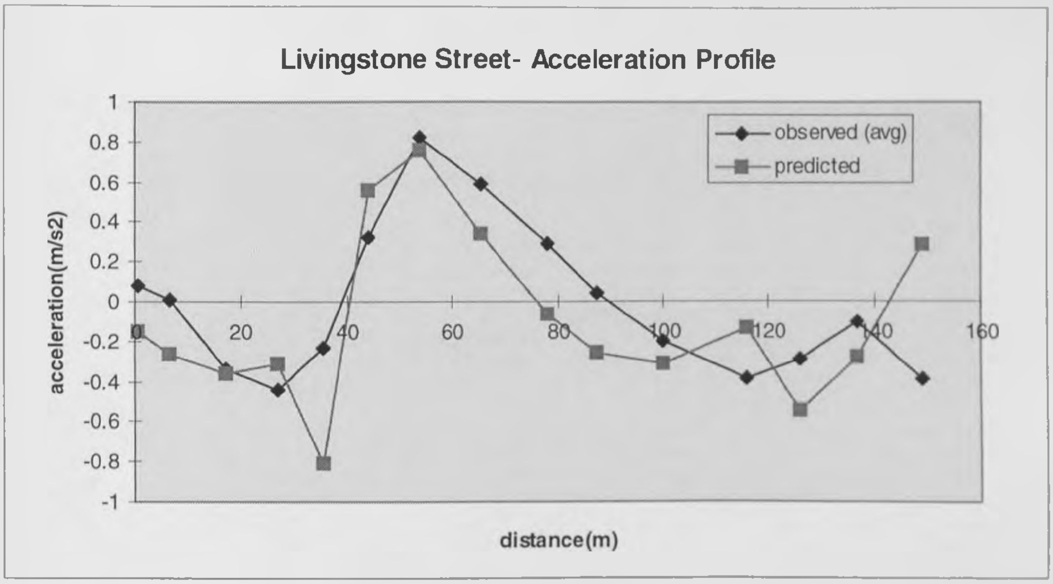


Figure 7.21: Modelled versus average acceleration profile - Livingstone Street

These discrepancies generally are consistent with those already commented on for the speed profiles. This is to be expected, since the acceleration profile prediction reflects the limitations of the speed profile model.

7.9 Conclusions

This chapter has presented the development of a speed profile model based on data collected at three traffic calmed links. A speed-distance relationship has been the basis to devise the model using in addition, other known variables such as the type and the location of the calming measures. The model has been developed with the weighted least squares regression (WLS).

The model coefficients for the dummy variables in Table 7.4, give an indication of the relative impact of the different measures: the table accounts for the greater impact (-6.71 km/h) followed by the hump (-4.48 km/h), the chicane (-2.01 km/h) and the cushion (-0.86 km/h) which accounts for the smallest impact. The range of values in the independent variables is also shown in Table 7.4.

Simplifications were inevitable in the calibration process in order to generate a simple model. One of the simplifications concerns the assumption of equal impacts from the chicanes. Assigning different impacts to the chicanes produced a negative coefficient for the first chicane and a positive one for the second chicane. The analysis of these coefficients shows that with respect to the first chicane, the second one allows higher crossing speeds which is consistent with the general trends. However, when those coefficients were applied to the regression equation in order to obtain speed values, their graphical representation indicated a distortion at the second chicane with increasing speeds at that point.

In general the model has presented a reasonable prediction capability for the calibration sites as graphically attested. The superimposition of modelled curves on observed profiles revealed that the modelled curves could have been any of the random observations in view of their similarity to the observed curves. Nevertheless, some discrepancies have been found. The first, and most common, relates to the accuracy of the entry speed prediction. It appears that there are speed ranges for which suitable predictions can be achieved.

The second drawback concerns maximum speeds between measures. Although all drivers did not attain maximum speed at the same data point, the average profile indicates differences with respect to this point with the model predicting maximum speeds for some sites occurring earlier than the observed point. These differences become even more noticeable in the acceleration profiles derived from the application of the speed profile model. In this respect the acceleration profile has also proved a reasonable prediction tool bearing in mind it will reproduce discrepancies encountered in the speed profile model as it is generated from the latter.

A third problem occurred specifically at Livingstone Street, where speeds around the second chicane were underestimated. However, this chicane, with its subsequent junction, displayed atypical impacts on speed in practice.

In summary, the calibration process has proved satisfactory but so far the predictive power of the model has been only analysed within the calibration sample. The next chapter considers its validation.

CHAPTER 8

MODEL VALIDATION

The speed profile model has been developed based on data collected at three sites namely Foxwood Lane West, Foxwood Lane East and Livingstone Street. This chapter introduces the validation of the model based also on data collected at three other sites: Fourth Avenue, Gale Lane and Townend Street. Data related to these roads have not been taken into account in the analyses conducted so far. In addition to the calculation of speeds at the 16 data points, the process of validation has required some data analysis in order to better understand the impacts of the measures encountered at those three new sites. This analysis has not been as extensive as that undertaken for the calibration sites.

The structure of this chapter has been set up to check (i) whether the model represents the other half of the calibration site data namely, Foxwood Lane East and Livingstone Street; and (ii) whether the model represents other sites namely Fourth Avenue, Gale Lane and Townend Street.

Following the validation process, the application of the model is demonstrated through hypothetical traffic calming schemes. Possible model output is also provided.

8.1 Validity of the Model Against the Other Half of the Calibration Site Data

The validity of the model will be verified by means of modelled against observed profiles using the reserved data (validation data set) from Foxwood Lane East and Livingstone Street. The original sample of these sites had been divided into two samples each, in order to validate the model against data not yet considered in the calibration process.

Hence, Figures 8.1 and 8.2 show the validation data plotted against the modelled profile, for an input speed of 33 km/h. These Figures do not introduce any new element and the same observations made in the previous chapter about the model prediction apply to this situation. In summary, Foxwood Lane East presents a well adjusted curve despite the maximum speed points occurring relatively earlier. However it should be noted that not all drivers attain maximum speed at the same point. The most remarkable feature in Livingstone Street relates to the flatter peak area of the model than the observed data, as already commented on in the previous chapter.

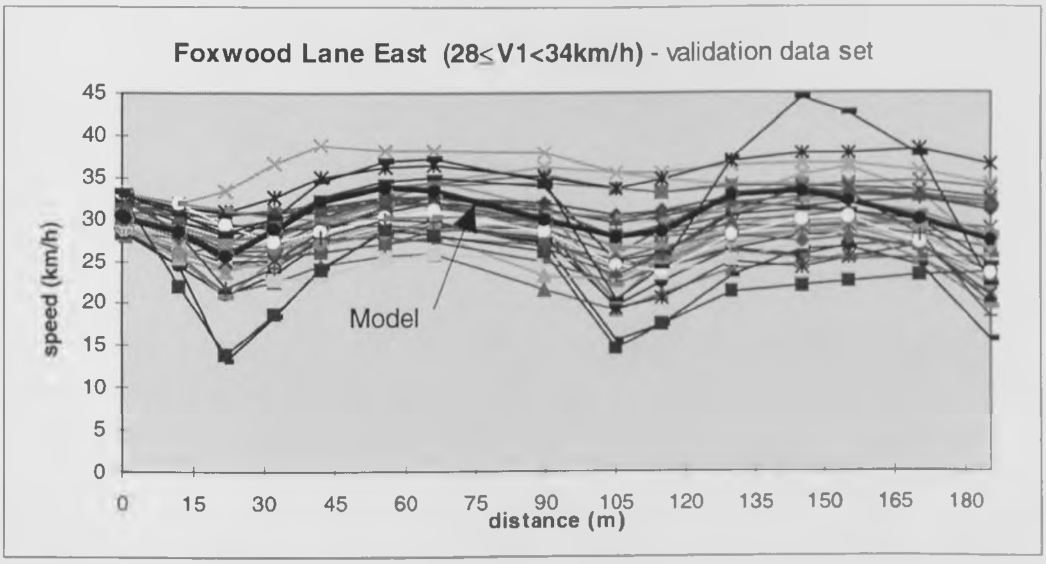


Figure 8.1: Modelled vs observed speed profiles - Foxwood Lane East

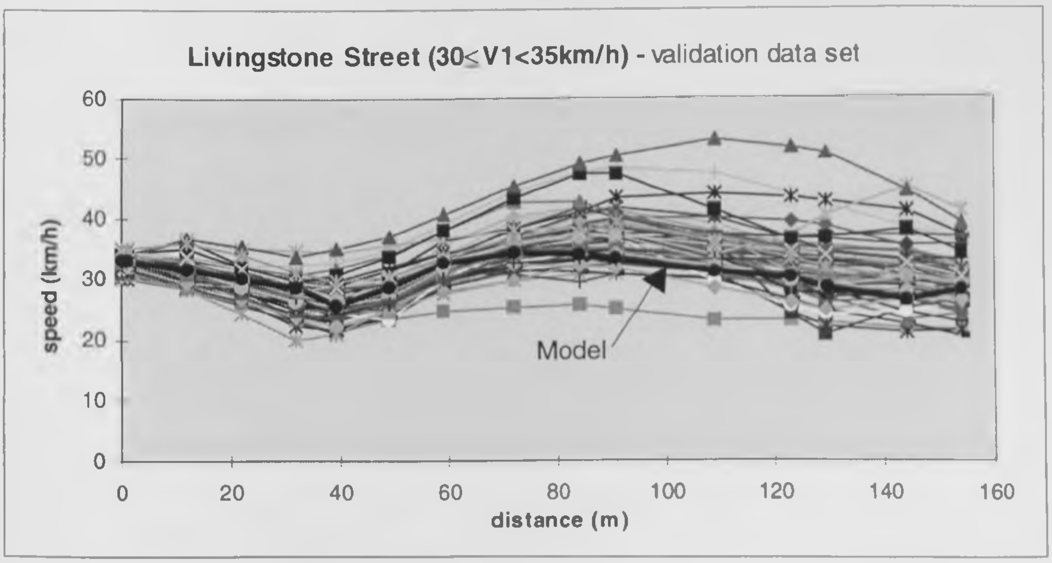


Figure 8.2: Modelled vs observed speed profiles - Livingstone Street

8.2 Validation Sites - a brief description

The validation sites present some similarities to the calibration sites concerning the combination of measures encountered at each site, so that Fourth Avenue resembles Foxwood Lane West; Gale Lane Foxwood Lane East; and Townend Street Livingstone Street, as shown next.

A table, a hump, and a cushion are the measures in Fourth Avenue, in this order at V3, V10 and V16 respectively. Gale Lane presents a series of cushions, and the surveyed link comprises three cushions at V4, V11 and V16. Townend Street also presents three measures, two chicanes (V5 and V10) and a hump plus a build-out to promote a sheltered parking area at the end of the link (V16). The position of chicanes has been specified as their mid length and this was mainly guided by the observation of the point at which the vehicles were travelling at lowest speeds. A complete description of the sites has been presented earlier in Chapter 4. The position of the sensors is indicated in Table 8.1 through the cumulative distance in the link. The highlighted cells indicate the location of the measures.

Table 8.1: Cumulative distance (in metres) - validation sites

Data points	FOURTH AVENUE distance (m)	GALE LANE distance (m)	TOWNEND ST. distance (m)
1	0	0	0
2	1.0	1.0	1.0
3	11.0	13.0	13.8
4	24.1	23.0	22.3
5	35.1	33.0	34.3
6	45.6	44.0	44.1
7	52.1	58.0	55.9
8	61.1	66.0	67.0
9	70.1	76.0	74.4
10	80.1	84.2	81.9
11	91.1	95.2	89.1
12	103.1	108.2	98.7
13	116.1	122.7	107.7
14	123.1	129.7	112.4
15	136.3	141.7	120.4
16	151.3	151.0	128.8

8.3 Model Curve Fit - Validation Sites

This section details the graphical representation of the speed profile model applied to the validation sites. The speed values have been obtained by substituting the partial distance values of *dt* and *df* and an input speed into the speed profile model equation defined in Table 7.4. This process was identical to that undertaken for the calibration sites. Data matrices containing the partial distance values and their higher order have been built for the validation sites in order to perform the calculations in a spreadsheet.

Following the same presentation structure of the previous chapter, firstly the speed profile model has been calculated for each validation site adopting an input speed V1 = 33 km/h. Hence, 16 speed values have been plotted and shown in Figures 8.3, 8.4 and 8.5 for Fourth Avenue, Gale Lane and Townend Street respectively.

The predicted entry speeds exhibit lower values than the input one (33 km/h): Fourth Avenue = 27.79 km/h; Gale Lane = 30.69 km/h; and Townend Street = 30.45 km/h. Fourth Avenue shows the most unfavourable prediction, probably as a result of the proximity of the first measure in relation to the link entrance (a situation similar to Foxwood Lane East).

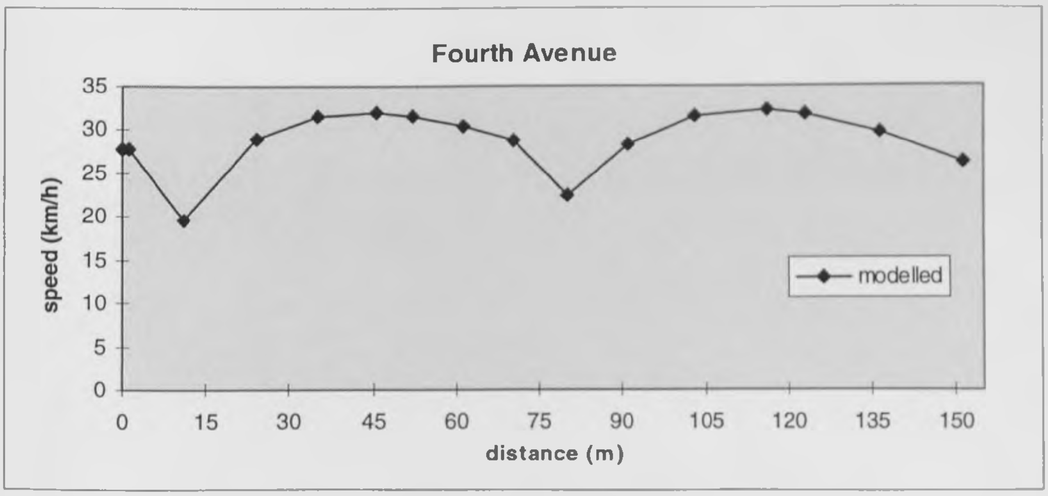


Figure 8.3: Modelled speed profile (V1= 33 km/h) - Fourth Avenue

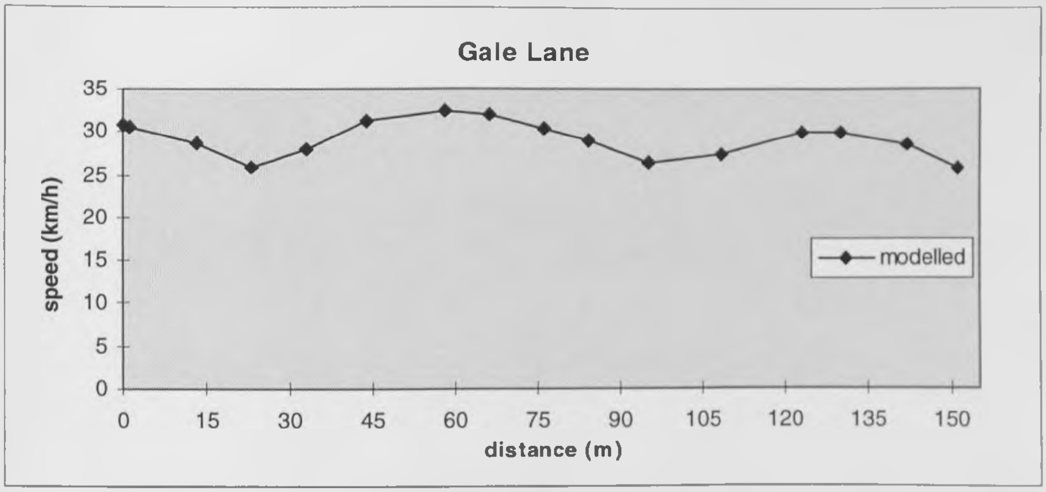


Figure 8.4: Modelled speed profile (V1= 33 km/h) - Gale Lane

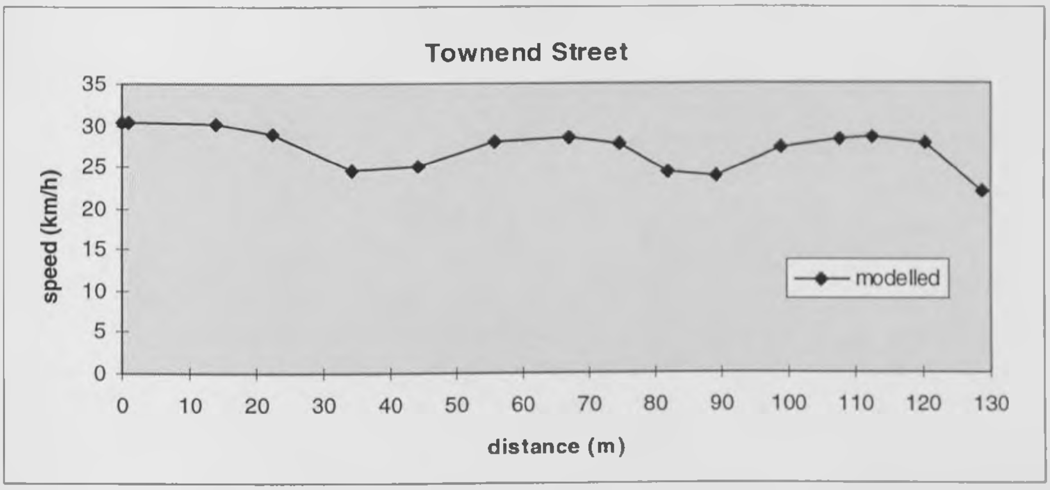


Figure 8.5: Modelled speed profile (V1= 33 km/h) - Townend Street

8.4 Goodness of Fit

8.4.1 Observed Vs Modelled Profiles

One approach to check the predictive power of the model covers the examination of the modelled speed profile, for an input speed of 33 km/h presented in the previous section, against the observed profiles for given entry speed ranges surrounding the input speed value. Figures 8.6, 8.7 and 8.8 depict the modelled profile (thick black line) superimposed on the observed data.

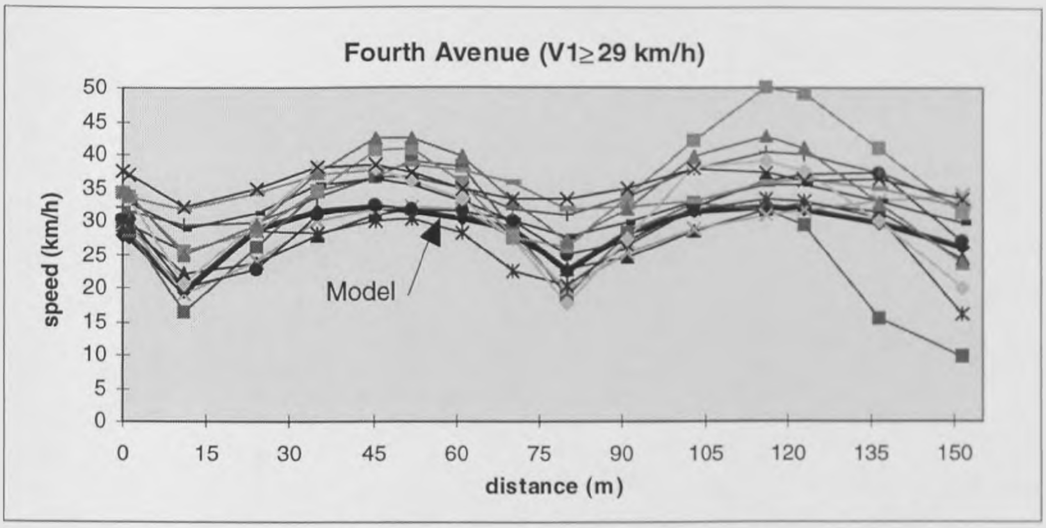


Figure 8.6: Modelled vs observed speed profiles - Fourth Avenue

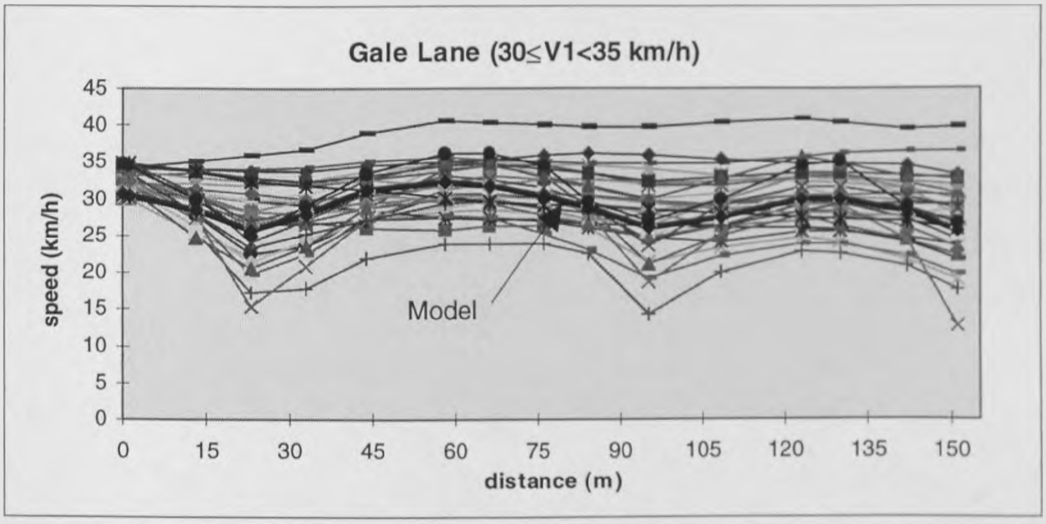


Figure 8.7: Modelled vs observed speed profiles - Gale Lane

For Fourth Avenue (Figure 8.6) the model follows the observed trends but the speed at the table (the first measure on the link) appears slightly underpredicted. The observed curves suggest more accentuated peaks than the modelled one. However, the observed profiles refer to the highest entry speed range found at this site. The modelled profile achieved for Gale Lane presents a good adjustment to the observed curves, but the point of maximum speed between the first and second cushion appears slightly earlier than the actual trends.

Contrasting with the above, the model has demonstrated its inadequacy to predict speeds for the two chicanes at Townend Street. This may indicate that these chicanes provoke a different impact on speeds than the chicanes used in the model calibration. According to the speed profile curves, the first chicane (at 34.3 metres from the origin) induces drivers to maintain or even increase speed rather than reducing it. The second chicane induces a slight speed reduction. Actually, the hump is the only feature which forces drivers to slow down, apparently to lower levels than the hump at the calibration site, Foxwood Lane West.

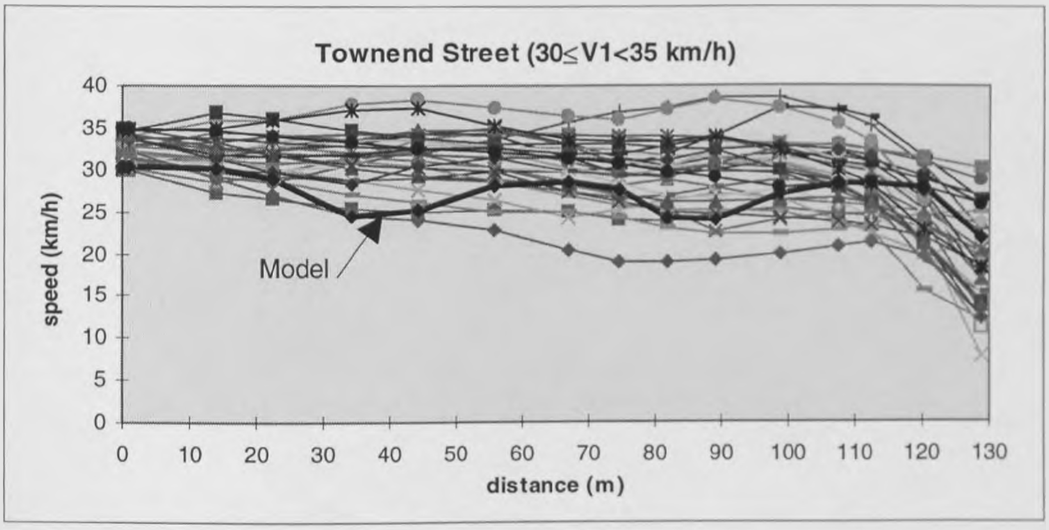


Figure 8.8: Modelled vs observed speed profiles - Townend Street

Due to the relatively big gap between predicted and observed entry speeds at Fourth Avenue as shown in Figure 8.6, another set of observed profiles, whose entry speed range comprises the entry speed resulting from the application of the model, has been presented in order to compare observed and modelled profiles in similar basis.

Although the predicted entry speed is within the actual entry speed range, Figure 8.9 presents similar trends to Figure 8.6. For instance, the model follows the observed trends also with less accentuated peaks and the speed at the data point after the table (the first measure) appears slightly overestimated as is the speed at the cushion (the third measure) whose slope is less steep than the observed ones.

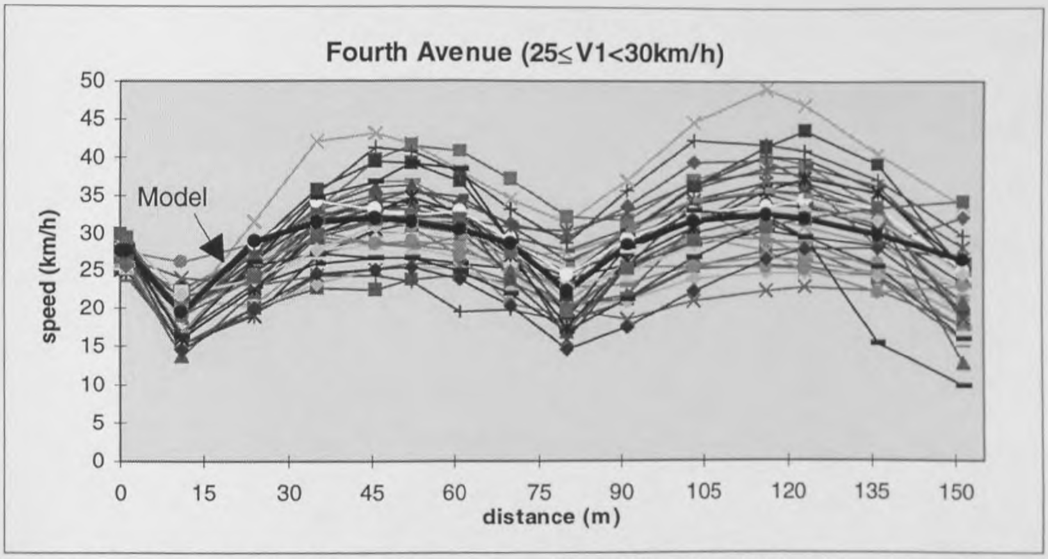


Figure 8.9: Modelled Vs observed speed profiles (25≤ V1<30 km/h) - Fourth Avenue

8.4.2 Average Speed Profiles

Similarly to the analysis of calibration sites, input speeds equal to the average speed calculated for the first data point (V1) have also been applied to the model equation, in order to compare average speed profiles against modelled speed profiles whose input speed is equal to the average entry speed. Each site has been associated with a distinct input speed since the average entry speeds vary between sites. Hence, the input speed adopted for each site is as follows:

Fourth Avenue	22.39 km/h;
Gale Lane	29.89 km/h;
Townend Street	30.25 km/h.

Figures 8.10, 8.11 and 8.12 compare these predictions with the average of the observed data. In general the average trends are well represented by the model predictions, apart from Townend Street.

In Figure 8.10, the average and predicted profile curvatures seem equal, in contrast to the results of the superimposition of selected profiles (Figure 8.6). However, the model underpredicts values for much of the range, except at the cushion (the last data point).

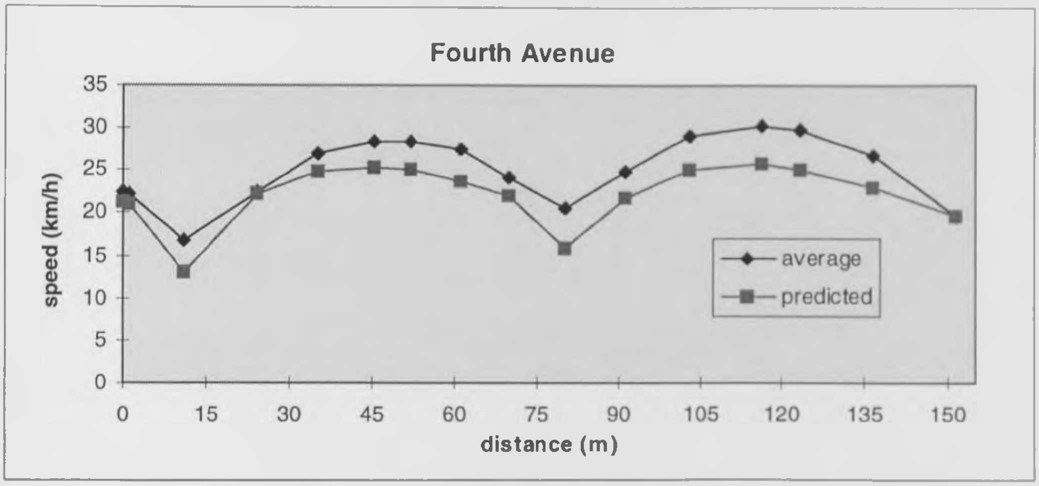


Figure 8.10: Average vs modelled speed profile - Fourth Avenue

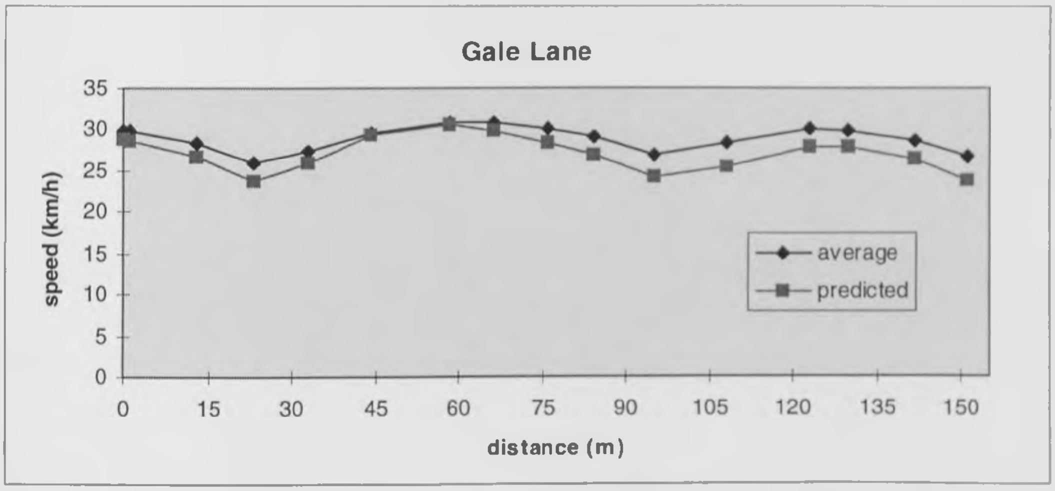


Figure 8.11: Average vs modelled speed profile - Gale Lane

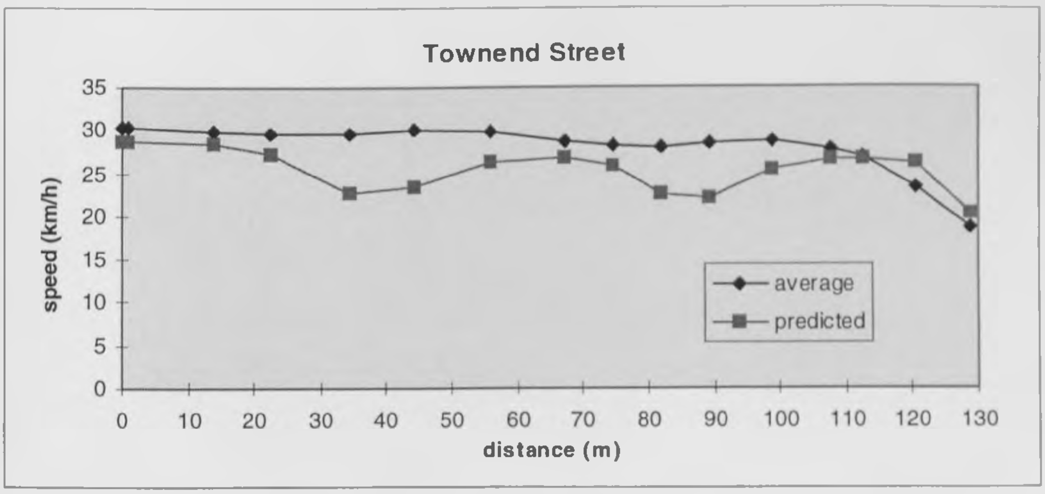


Figure 8.12: Average vs modelled speed profile - Townend Street

Gale Lane (Figure 8.11) represent a good prediction. The model slightly underpredicts speeds by a constant value. The only exception appears at the acceleration length after the first cushion, before reaching maximum speed. This discrepancy seems to be responsible for the transference of the maximum speed data point to a previous point on the graph, also observed for Foxwood Lane East data.

For Townend Street, the average profile shown in Figure 8.11 reveals no impact on speeds from the first chicane and a slight one from the second chicane. Not surprisingly the model fails to predict this lack of impact. Conversely, the hump induces a somewhat higher deceleration rate than that one predicted by the model. This is probably because the model has assumed an impact of the chicanes which in practice does not occur.

8.4.3 Sensitivity Analysis

The analyses conducted in this section make use of two statistical procedures: (a) residual analysis; and (b) predictive capability analysis, which are other ways of testing the goodness of fit of the model for the calibration site data.

The predicted profile curves have been calculated by feeding the observed entry speed values into the model equation. Residuals have been obtained from the comparison of observed and predicted speeds, in the same manner as Chapter 7.

Residual Analysis

The analysis of standardised residuals obtained as mentioned above, has enabled the detection of outliers by data points. The high incidence of outliers concentrates at the location of the measures as shown in Table 8.2. The scattergrams of residuals of high incidence data points reveal a random distribution.

Table 8.2: Number of outliers by data points - validation sites

Site	Exp	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
FA	8	3	2	21	6	0	0	0	1	2	15	0	0	0	1	2	39
GL	8	14	8	1	13	3	1	0	0	0	0	7	0	1	2	1	19
TS	12	3	2	0	0	13	4	0	1	1	0	3	0	1	1	26	39

key: FA = Fourth Avenue; GL = Gale Lane; TS = Townend Street
Exp = expected number of outliers within 95% confidence level

The absolute error based on the difference between observed and predicted entry speed values, has been used to determine the speed ranges for which the model yields the least errors. The confidence interval for the 95% level found for V1 has also been assumed as the least prediction error. The speed intervals which present errors within the confidence intervals are demonstrated in Table 8.3 below.

Table 8.3: Input speed intervals for optimum prediction - validation sites

Sites	Confidence intervals for entry speed (V1)	Optimum prediction speed ranges (km/h)
Fourth Avenue	± 0.77	17.39 - 21.35
Gale Lane	± 0.97	24.35 - 29.47
Townend Street	± 0.61	24.67 - 27.89

Average entry speeds found for all sites are above the optimum speed range obtained through the absolute error analysis.

Predictive Capability Analysis

A simple manner to test the predictive capability is through the graphical representation of actual versus predicted speed. Observations scattered along a 45° line passing through the origin indicate a good predictive power. In other words, predicted values are linearly related to the actual values through a relationship whose intercept is zero and the slope is one.

There is a general trend in the model prediction as the scattergrams show (Figures 8.13-17): the plotted points follow a line, usually the line predicted for the entry speed V1, which does not coincide with the expected 45° line. In the case of Gale Lane (Figure 8.13), the line predicted for V1 presents an intercept ≅ 10.23 which corresponds to the output of the model equation for an input speed of zero. This general trend emphasises what has been commented on earlier: for lower actual speeds the model tends to overpredict whereas it underpredicts for higher speeds.

The scattergrams for Fourth Avenue in Figures 8.15 and 8.16 follow the general trends. However, data points V9 to V16 appear even more underpredicted. Among the measures, the hump at V10 and the table at V3 appear underpredicted for most of the speed values; the cushion at V16 presents a more balanced situation and the underprediction is more frequent for higher speeds but for lower speeds the prediction is overestimated sometimes.

It should be noted that the scattergrams for Townend Street in Figure 8.17 only consider the end of the link (from V13 to V16) as the chicanes have demonstrated that they cannot be reliably predicted by the model. The plotted points appear more uniformly distributed above and below the 45° line, apart from V16 (the hump) for which lower speeds are overpredicted.

In summary, for lower speeds the model overpredicts whereas for higher speeds it underpredicts. Average speed values are the best region for speed predictions. Gale Lane presents a good overall prediction, as does the final portion of the link of Townend Street. Conversely, speeds at the hump and the table at Fourth Avenue are mostly underpredicted. Another interesting point to highlight refers to the slightly less accentuated shape of the curves in Fourth Avenue. In fact, the analysis of V6 to V8 and V13 to V15 shows a concentration of underpredicted speeds at these data points mainly for actual speeds greater than 25 km/h.

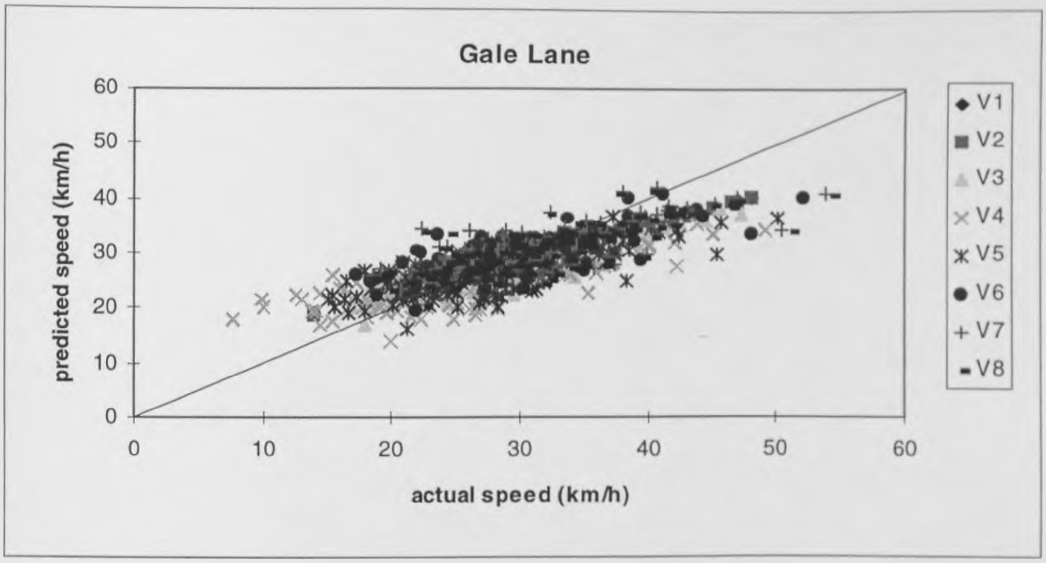


Figure 8.13: Actual vs predicted speeds - Gale Lane (V1 to V8)

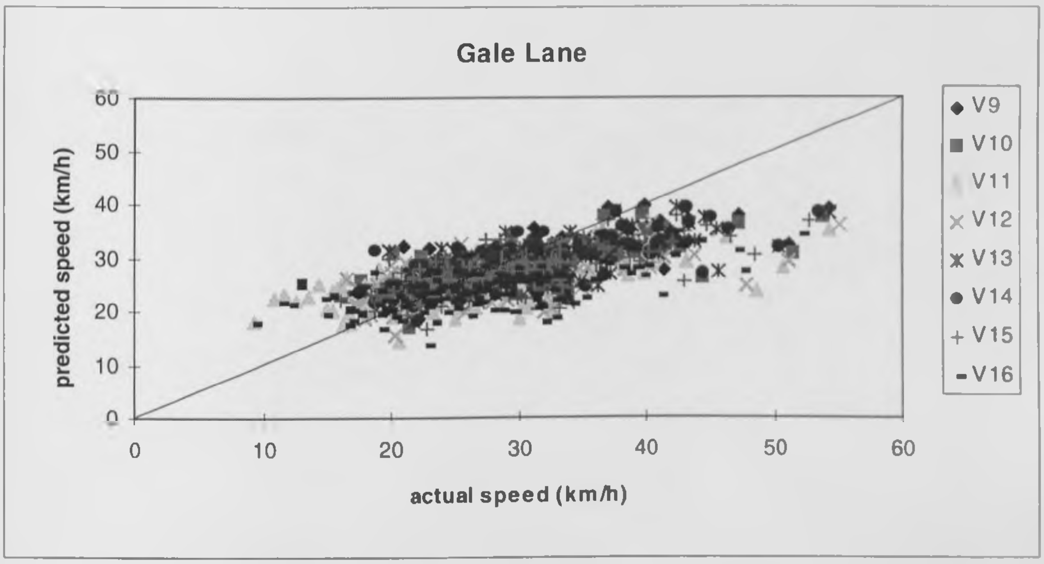


Figure 8.14: Actual vs predicted speeds - Gale Lane (V9 to V16)

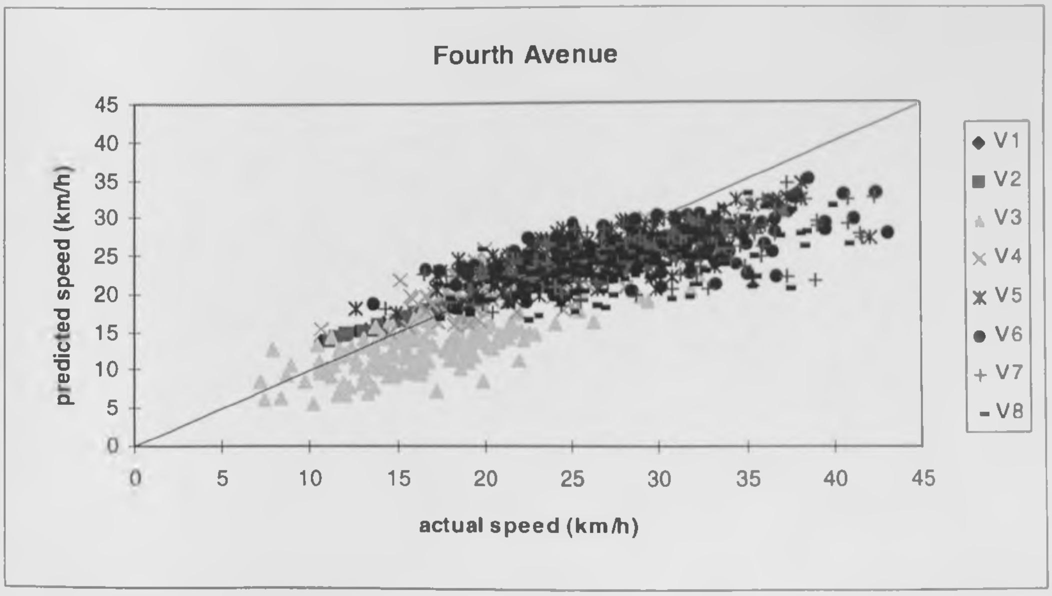


Figure 8.15: Actual vs predicted speeds - Fourth Avenue (V1 to V8)

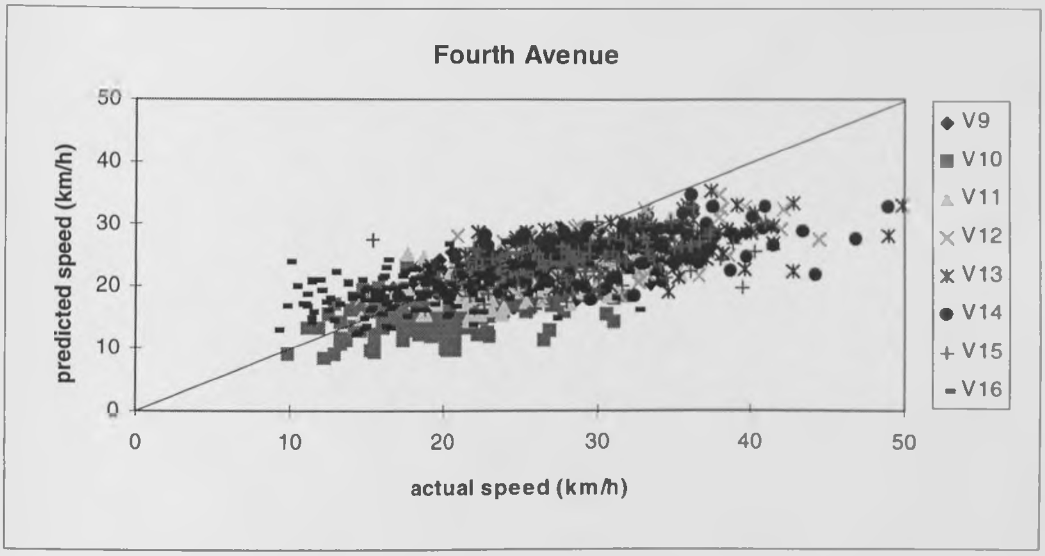


Figure 8.16: Actual vs predicted speeds - Fourth Avenue (V9 to V16)

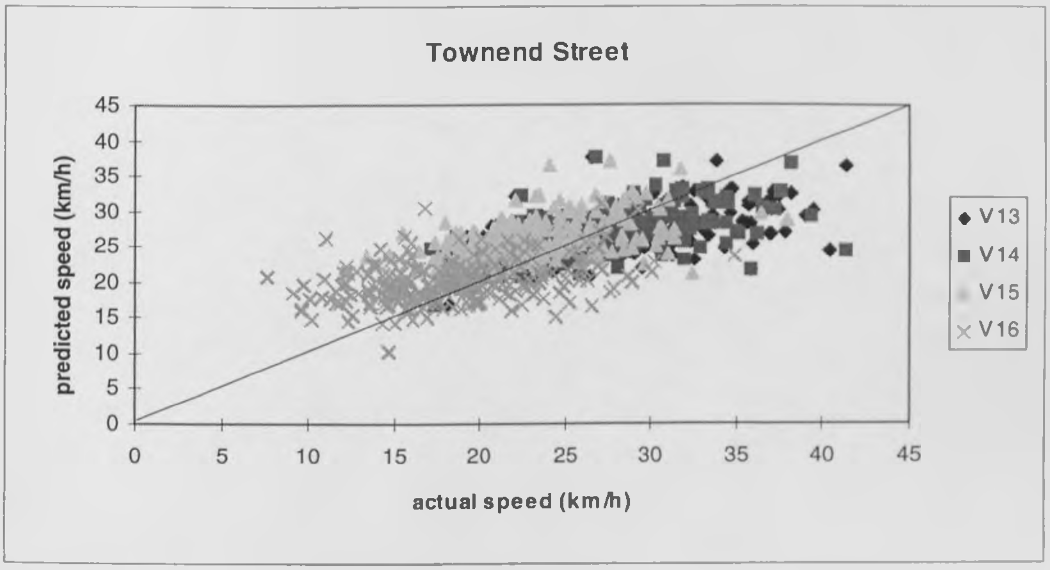


Figure 8.17: Actual vs predicted speeds - Townend Street (V13 to V16)

8.5 A Brief Assessment of the Surveyed Measures

This section aims at introducing more information about each of the measures encountered in the surveyed links, firstly by presenting the layout and dimensions of the measures and secondly by their speed distribution.

8.5.1 Layout and Dimensions

Layout and dimensions of measures are shown in Table 8.4 as reported by Layfield et al (1994) and Abbott et al (1994) while studying speed cushions at Foxwood Lane, Fourth Avenue and Gale Lane. The dimensions of chicanes have been presented separately because of the different design parameters.

Table 8.4: Layout and measure dimensions - cushions, tables and humps

Measure layout	Width		Length		Height	Ramp gradients	
	PW (mm)	OW (mm)	PL (mm)	OL (mm)	(mm)	on/off	side
CUSHIONS **single pair:**							
Gale Ln	1100	1700	800	2000	75	1:8	1:4
Fourth Av	1200	1800	2300	3500	75	1:8	1:4
three abreast:							
Foxwood Ln E	1050	1650	1300	2500	75	1:8	1:4
Foxwood Ln W	1050	1650	1300	2500	75	1:8	1:4
TABLES							
Foxwood Ln W	-	-	2500	3700	75	1:8	-
Fourth Av	-	-	2500	3740	75	1:8.3	-
HUMPS							
Foxwood Ln W	-	-	-	3700	75 [78]	-	-
Fourth Avenue	-	-	-	3700	75 [92]	-	-
Townend St	-	-	-	3700	[85]	-	-

key: PW = platform width; OW = overall width;
PL = platform length; OL = overall length
[ ] = actual average height measured by York City Council

The description of the physical dimensions of chicanes in Table 8.5 has been based on the parameters adopted by Sayer and Parry (1994). In this particular case the dimensions have been obtained from the drawings provided by York City Council. As a result they may not fully represent the on-site applications, which may have required some simplifications. Hence, parameters may only be used as comparative elements among chicanes. According to the type, a single chicane is a right/left or left/right horizontal deflection and a double one comprises two opposite horizontal deflections, for instance left/right quickly followed by right/left (see Figure 8.18). Build-out length is the length between two deflections (double chicane only).

Table 8.5: Chicanes layout and dimensions

Sites	Chicane	Type	Deflection	Width (m)	Stagger length (m)	Build-out length (m)
Livingstone St.	**Ch 1**	single	R/L	3.6	11.6	-
	Ch 2	single *	L/R	3.6	8.0	-
Townend St.	**Ch 1**	single	R/L	3.0 - 3.8	11.0	-
	Ch 2	double	L/R R/L	4.5	3.5	3.0

* the design resembles a double chicane but the road layout after the build-out allows vehicles to go ahead without steering

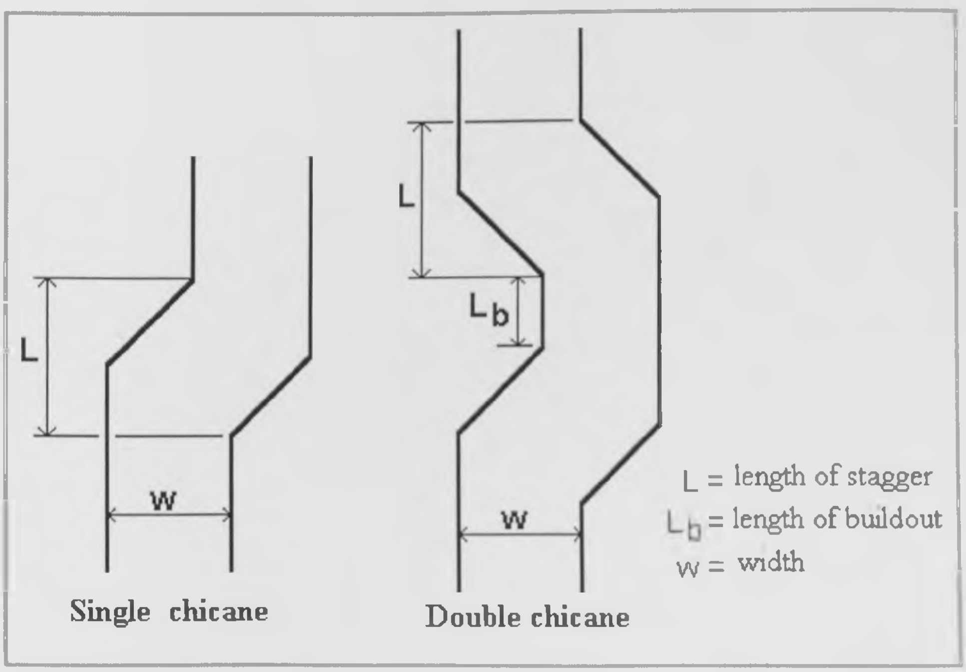


Figure 8.18: Single and double chicane layout

8.5.2 Speed Distribution

For the presentation of speed distributions, measures have been grouped by site category (calibration and validation) in the box plots shown in Figures 8.19 and 8.20. Although the calibration site measures have already been presented according to individual sites in Chapter 5, these Figures provide an easy visual comparison among all measures.

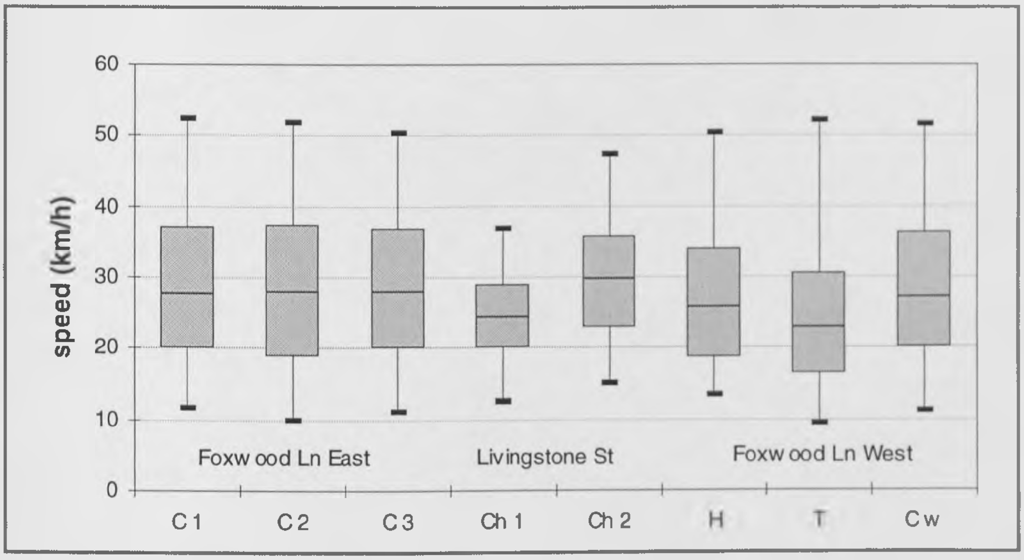


Figure 8.19: Minimum, 15th%ile, median, 85th%ile, and maximum speeds for measures at the calibration sites

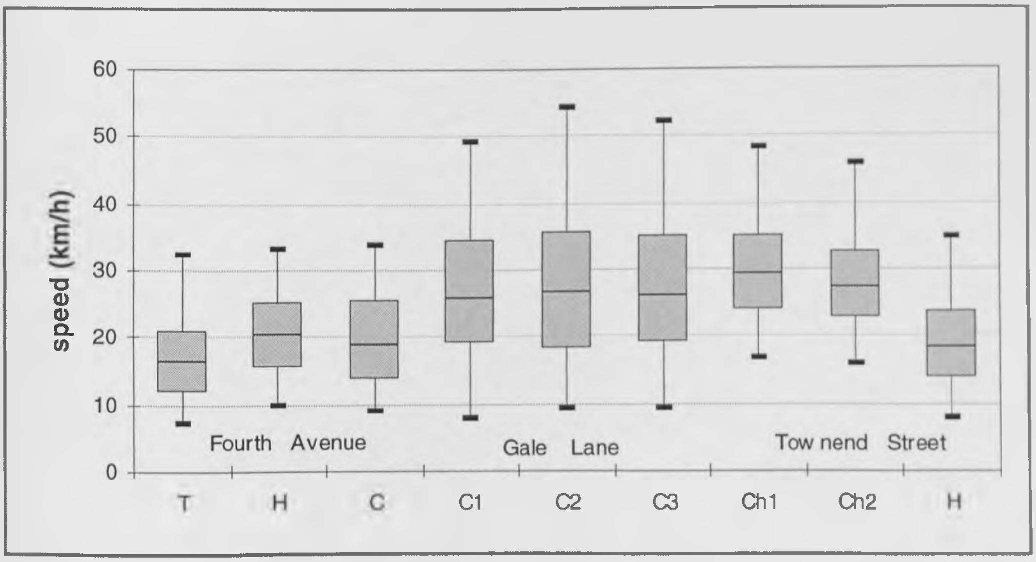


Figure 8.20: Minimum, 15th%ile, median, 85th%ile, and maximum speeds for measures at the validation sites

Cushions exhibit the greatest similarities in speed distributions apart from the cushion at Fourth Avenue. Speed variability at the hump and the table at the calibration sites (Foxwood Lane West) is bigger than those at the validation sites. The small size of the boxes also indicate this. Chicanes present similar speed variability apart from the first chicane (Ch1) in Livingstone Street which presents lower speeds.

8.5.3 Consistency of Crossing Speeds

The main discrepancies found during the model validation using the validation sites refer to the predictive capability at the calming measures. The most remarkable inadequacies are related to the chicanes in Townend Street. Speeds along traffic calmed links are affected by the input speeds, spacing and the type of measure, as suggested by the speed profile model. Nevertheless, the search for an explanation for the discrepancies has led to the examination of the isolated effect of each measure on speeds in addition to the previous visual comparison of speed distributions. This procedure solely considers speeds at the measures and tests if the mean speed crossing at one measure is equal to the mean at another one by applying the t-test in the same manner as Chapter 6.

Chicanes

T-tests assuming unequal variances have been conducted among the four chicanes and the test summary is presented in Table 8.6 below. The comparison of t stat and t critical values results in the rejection of the equivalence of means for all pairs apart from the pair chicane 1-Townend Street and chicane 2-Livingstone Street. Presumably this equivalence reflects the minor impact of these measures on speeds.

According to these results, there appear to be three types of chicanes, but one of them was only known after dealing with the validation site data. The assignment of distinct impacts to the chicanes during the model development process would probably have produced in the graphical representation of the speed profile curve for Townend Street, the same distortion found for Livingstone Street, as mentioned in Chapter 7.

Table 8.6: T-test summary for chicanes (Livingstone St. and Townend St.)

Chicanes	Mean	Variance	Cases	Df	t stat	t critical
Ch1 (TS)	29.70	27.83	240	478	3.788	1.965
Ch2 (TS)	27.86	24.43	240			
Ch1 (TS)	29.70	27.83	240	350	0.147	1.967
Ch2 (LIV)	29.61	37.58	179			
Ch2 (TS)	27.86	24.43	240	352	-3.055	1.967
Ch2 (LIV)	29.61	37.58	179			
Ch1 (TS)	29.70	27.83	240	413	11.508	1.966
Ch1 (LIV)	24.28	18.95	179			
Ch2 (TS)	27.86	24.43	240	414	7.570	1.966
Ch1 (LIV)	24.28	18.95	179			

key: TS = Townend Street; LIV = Livingstone Street

From this result it may be concluded that the impact of chicanes on speeds is highly dependent on the design of the device and, therefore chicanes should have a different treatment in the modelling process dependent on their design.

Humps

Among the surveyed sites there are three humps, namely at Foxwood Lane West, Townend Street and Fourth Avenue. Testing the equivalence of means for humps through t-tests has indicated no equivalence among the three humps under consideration as reported in Table 8.7 below.

The mean speeds obtained for humps at Foxwood Lane West and Fourth Avenue are consistent with the values reported by Layfield et al (unpublished). Therefore, the difference encountered may be related to site to site variation. The difference between average speeds recorded before the implementation of humps, 32.1 mph at Foxwood Lane West and 28.3 mph at Fourth Avenue (source: Layfield et al, unpublished) is maintained after the installation of humps, even though they have different actual average heights (see Table 8.2).

Table 8.7: T-test summary for humps

Humps	Mean	Variance	Cases	Df	t stat	t critical
H (TS)	18.46	22.45	240	358	-4.332	1.967
H (FA)	20.51	21.47	165			
H (TS)	18.46	22.45	240	232	-12.138	1.970
H (FW)	26.62	54.77	153			
H (FA)	20.51	21.47	165	252	-8.742	1.970
H (FW)	26.62	54.77	153			

key: TS = Townend Street; FA = Fourth Avenue; FW = Foxwood Lane West

Tables

The surveyed links comprise only two speed tables, at Fourth Avenue and at Foxwood Lane West. In the same manner as above, a t-test has been conducted to test the equivalence of means at the tables. The results in Table 8.8 attests to the rejection of the null hypothesis, that is the means cannot be accepted as equal.

Table 8.8: T-test summary for tables (Fourth Avenue and Foxwood Lane West)

Table	Mean	Variance	Cases	Df	t stat	t critical
T (FA)	16.74	19.66	165	248	-10.198	1.970
T (FW)	23.69	52.83	153			

key: FA = Fourth Avenue; FW = Foxwood Lane West

Once more the mean speeds are consistent with the observations of Layfield. Hence, the difference may be due to variations between sites as there is no significant difference on dimensions. Furthermore, speed measurements before the implementation of calming schemes in these roads act as evidence of differences between sites: Foxwood Lane West had a mean speed of 31.8 mph whereas Fourth Avenue was 25.9 mph (source: Layfield et al, unpublished). These speeds were measured at the actual location of tables.

Cushions

The number of cushions encountered at the surveyed links is significantly greater than the remainder of calming measures - there are eight cushions within the sites. For the sake of simplification, the outcome of the t-tests conducted among cushions has been presented in the form of a matrix which indicates whether there is equivalence among pairs. Average speed at the cushions (in km/h) is also presented in Table 8.9 in the first column, below the identification of cushions.

Table 8.9: Equivalence of cushions

	V10 (FE)	V16 (FE)	V16 (FW)	V4 (GL)	V11 (GL)	V16 (GL)	V16 (FA)
V4 (FE) 28.51	✓	✓	✓	≠	✓	≠	≠
V10 (FE) 28.17		✓	✓	≠	✓	✓	≠
V16 (FE) 28.52			✓	≠	✓	✓	≠
V16 (FW) 27.90				✓	✓	✓	≠
V4 (GL) 26.36					✓	✓	≠
V11 (GL) 26.97						✓	≠
V16 (GL) 26.79							≠
V16 (FA) 19.58							

key: FE = Foxwood Lane East; FW = Foxwood Lane West; GL = Gale Lane; and FA = Fourth Avenue

From Table 8.9, the cushion in Fourth Avenue cannot be accepted as equivalent to any other cushion. In fact, its dimensions differ from the remainder of cushions (see Table 8.4). The overall width is 0.10 to 0.15 metres greater, hence it is more severe. There is an equivalence within cushions in Gale Lane, however V4 is not equivalent to the cushion in Foxwood Lane East. The dimensions of these cushions are quite similar, but the overall length for Gale Lane cushions is 0.05 metres shorter.

8.5.4 Discussion

Measures of the same type, layout and dimensions have demonstrated slightly different impacts through their speed distributions and average speed at the device, presumably as a result of site to site variations. In particular, differences in impacts would be expected from the model derived in Chapter 7 as a result of differences in input (or before) speed. Moreover, differences in the average height of the humps (FW and FA) seem to indicate a minor effect as the speed differentials between before and after measurements are similar for these sites. Cushions have shown more consistent impacts, whereas the impacts from chicanes are highly dependent upon their design.

8.6 Model Validity Assessment

It should be stressed that this is an exercise to assess the validity of the speed profile model against the data collected at the validation sites in contrast to the visual validation of the model against the observed individual speed profile curves carried out in sections 8.4.1 and 8.4.2. Hence, the validity of the model has been checked against a new relationship of the same form of the model derived based on the validation site data. Hence, a new database matrix, of the same format as that in Table 7.1, containing data from the validation sites Fourth Avenue and Gale Lane was used to run a regression model. The Townend Street data has been excluded from this relationship because of the two chicanes whose speed reduction effects are negligible.

The new relationship was initially derived through the ordinary least squares method. Not surprisingly, the resulting model presented heteroscedasticity which was corrected by applying weighted least squares regression in the same manner as described in Chapter 7. The final form of the relationship differs from the original speed profile model in that the new relationship includes less variables than the original one: df^3 and the dummy variable for *hump* did not present significant contributions to the model; *chicane* was obviously not included.

Table 8.10 presents the main regression output of this new relationship together with the output of the speed profile model (original model). A straight comparison of the coefficients presented in Table 8.10 is not proper because the relationships do not involve the same variables. Therefore, the comparison of these relationships through their graphical representation appears more appropriate.

Table 8.10: Regression output of the validation site data relationship compared to the original model

	Validation relationship	**Original model (calibration)**
Variable	**Estimate**	**Estimate**
dt	0.384	0.223
df	0.464	0.779
dt^2	-0.0032	-0.0012
df^2	-0.0039	-0.0137
df^3	-	8.52E-06
H hump	-	-4.483
T table	-3.156	-6.710
C cushion	0.631	-0.856
Ch chicane	-	-2.011
V1	0.637	0.622
(constant)	-7.249	-8.733
Multiple R	0.764	0.740
R square	0.584	0.547
Adjusted R square	0.584	0.546
Standard error	1.979	1.984

Using the coefficients for the validation data provided in Table 8.10, a speed profile curve can be obtained for Fourth Avenue and Gale Lane for an entry speed of 33 km/h. These two curves have been presented together with the calibrated speed profile curves in Figures 8.21 and 8.22.

Figures 8.21 and 8.22 attest that the calibration and validation relationships present similar predictive capability and the differences encountered are typically under 3 km/h, which is reasonable given that the relationships were derived from different data sets which have demonstrated differences in the impact of measures of the same type.

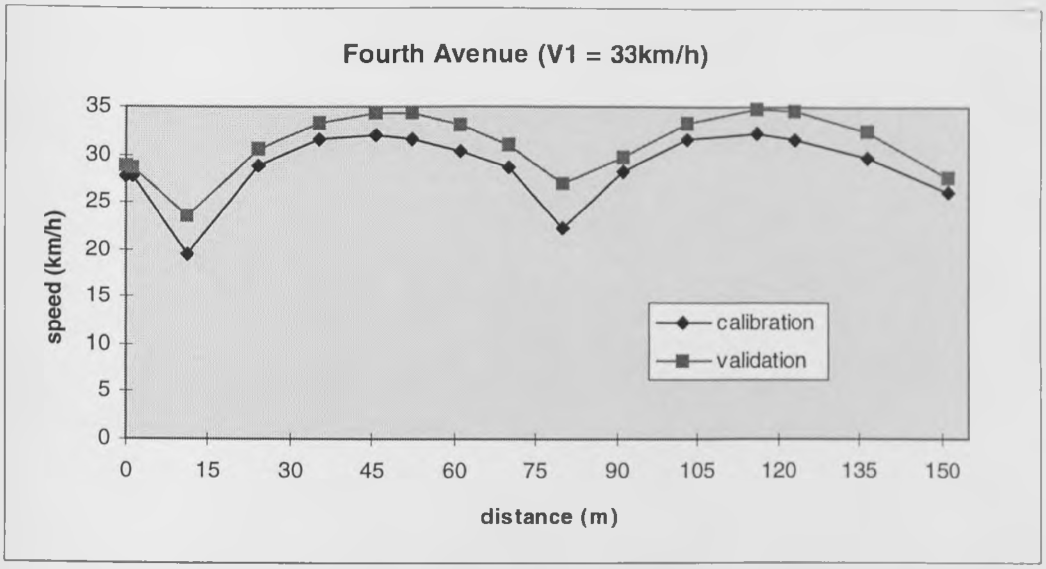


Figure 8.21: Fourth Avenue - comparison of calibration and validation relationships

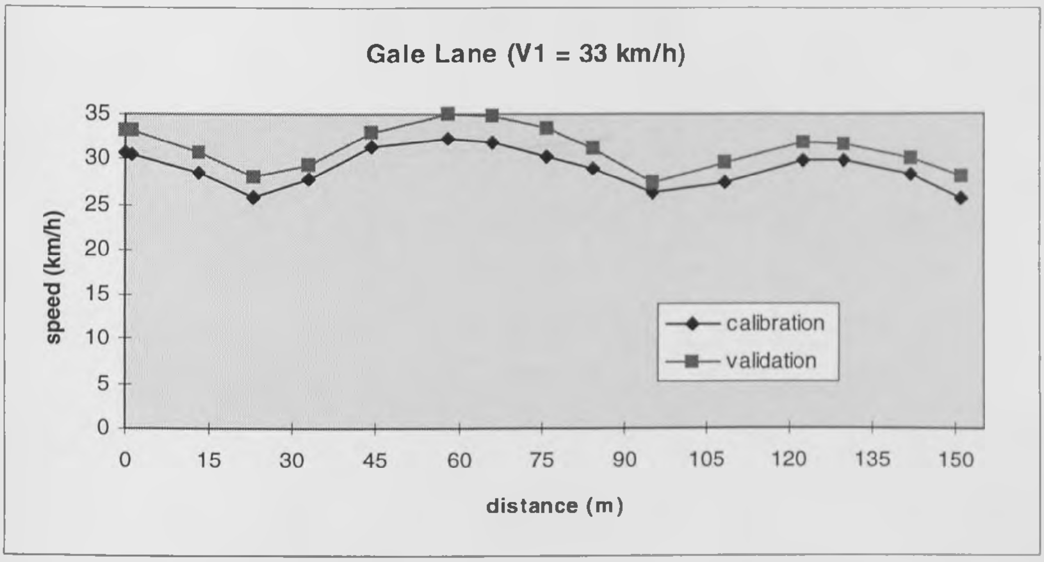


Figure 8.22: Gale Lane - comparison of calibration and validation relationships

8.7 Applications of the Speed Profile Model

The speed profile model has been derived to take into account four types of measures, namely speed humps (flat-topped and round topped), speed cushions and chicanes. It needs to be borne in mind that chicanes considered in any model application should have similar dimensions and layout to the first chicane in Livingstone Street. The remainder of the measures should have similar dimensions and layout to those used in the calibration process.

Three variables need to be fed into the model equation to predict speed profiles: the input speed, the spacing between measures (which leads to *distance to* and *distance from*), and the type of measure.

The speed profile model has a quite lengthy expression which may, at first, discourage its use. However, when a database matrix is in a spreadsheet, such as Excel 5.0, the work is reduced to a minimum. Moreover, Excel offers great flexibility through its integrated processing which enables any alteration to the database matrix to be simultaneously amended in the formulae and also in the graphs embedded in the spreadsheet. Therefore, various combinations of spacing and measures can be assessed by a simple substitution of values. An example of the use of an Excel spreadsheet with the respective formulae is presented in Appendix C.

Three hypothetical traffic calming schemes have been created in order to demonstrate practical application of the model. It should be noted that combinations of spacing and type of measures are unlimited and these examples do not attempt to and cannot cover all possibilities. The hypothetical schemes involve humps, tables, cushions and chicanes with spacings varying from 55 to 90 metres. Speed profiles in Figures 8.23, 8.24 and 8.25 were obtained for an input speed of 33 km/h.

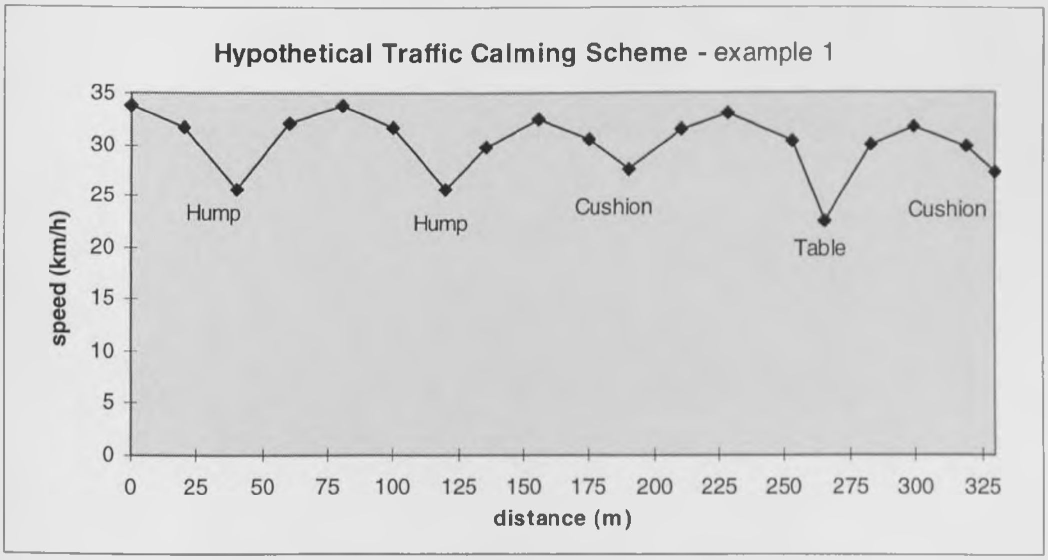


Figure 8.23: An example of the model application

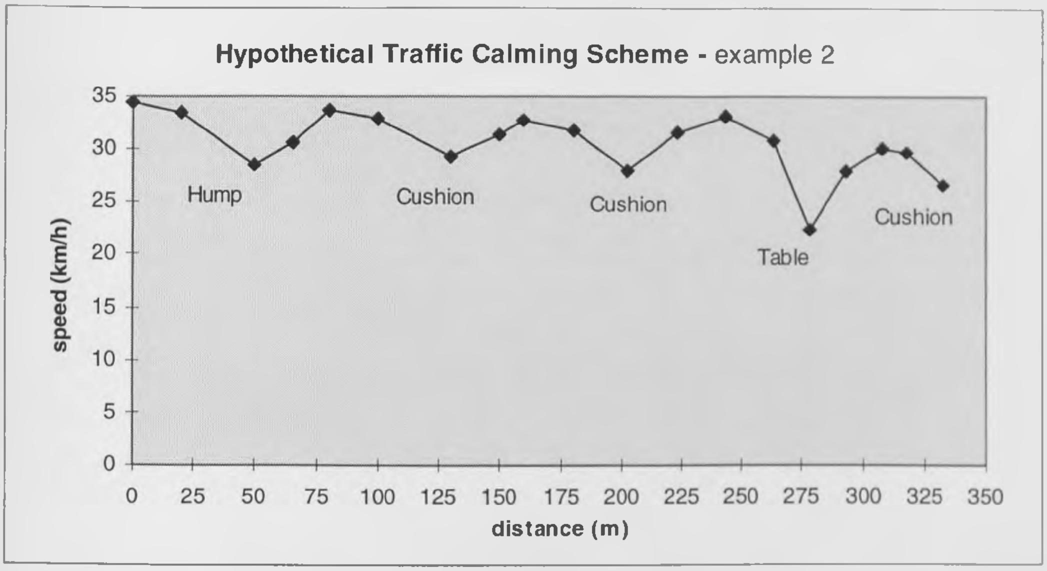


Figure 8.24: Model application - example 2

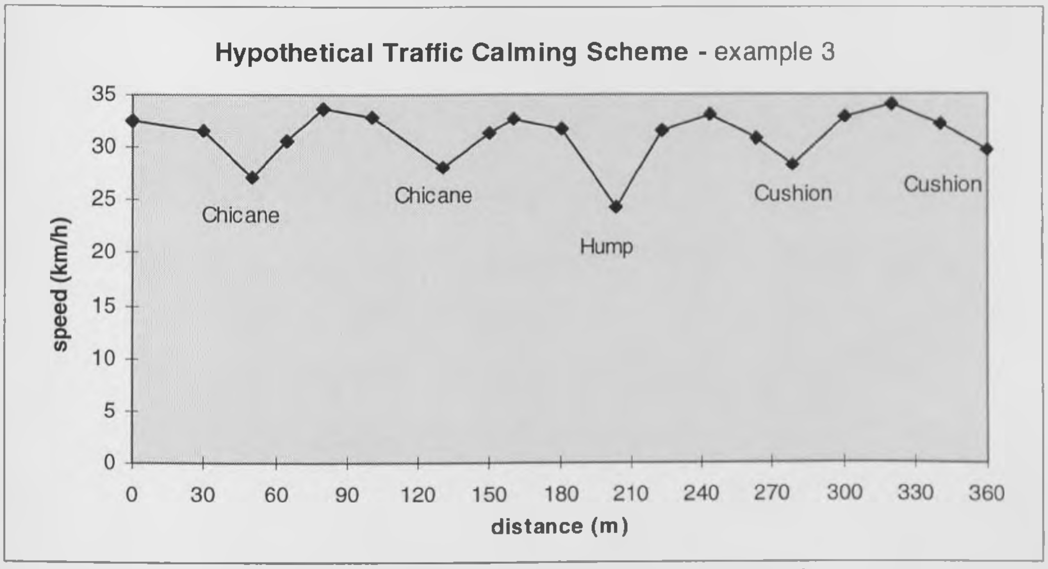


Figure 8.25: Model application - example 3

Usually maximum speeds between measures (and of course speeds at the measures) are the variables of most interest, hence the concentration of data points around 50 to 60% of the spacing would produce the desired output in terms of the identification of maximum speeds.

8.7.1 Possible Model Output

Output from the application of the model can be twofold:

(i) an engineering approach envisaging safety issues mainly assessed through the speed reduction achieved by a specific traffic calming scheme; and

(ii) an economic approach which is an extension of the engineering approach, by means of social cost-benefit analysis to assess whether the predetermined objectives, measured in terms of speed reduction levels, will produce gains in environmental aspects which justify the investments.

8.8 Conclusions

The speed profile model, developed under a speed-distance relationship, has been checked in order to test whether it represents (a) the other half of the calibration data and (b) the validation sites: Fourth Avenue, Gale Lane and Townend Street.

The model fits the validation data from the calibration sites, Livingstone Street and Foxwood Lane East, well. In this stage of the model validation the same patterns of the calibration process were observed and no new element was added to the previous analysis.

With respect to the validation sites, the model presents quite a good fit for Gale Lane and for Fourth Avenue. Discrepancies in the entry speed prediction were observed for both sites and Fourth Avenue shows the more unfavourable prediction. In general, the optimum entry speed prediction has proved to be restricted to certain speed ranges and outside those ranges results were overestimated for lower input speeds and underestimated for higher input speeds.

In the calibration process, maximum speeds between measures have been predicted at a different data point in comparison to the average profile. Conversely, Fourth Avenue and Gale Lane presented a more realistic prediction for maximum speeds, except for the maximum speed between the first and second cushion in Gale Lane which appeared slightly earlier than the actual trends.

The overall prediction for Fourth Avenue and Gale Lane is very reasonable, and more consistent for Gale Lane presumably as a result of more similar speed distributions at the cushions in comparison to the calibration sites. For Fourth Avenue the model generally underpredicts by around 3 km/h (average profiles) and the observed curves suggest more accentuated peaks than the modelled one.

The model does not provide a good fit for Townend Street except for the hump, largely because the chicanes have no effect on speeds. Therefore, chicanes need a special consideration to be reliably predicted by the model due to their wide design variation. The sample of chicanes used in this study has demonstrated diverse speed reduction levels, suggesting that chicanes located at junctions (T or X-junctions) are likely to generate less impact on speeds as the design cannot be so restrictive as those for straight sections of roads.

The assessment of the speed distributions at the measures has indicated some differences between measures of the same type. The lower average speed at the cushion in Fourth Avenue may reflect its distinct dimensions in comparison to the remainder of cushions. Humps and tables have also shown distinct average speeds when comparing calibration and validation sites. Differences between measures of the same type may be mainly attributed to variations between sites as the speed differential between before and after speed measurements has been maintained, for instance at Fourth Avenue and at Foxwood Lane, in addition to the geometry and layout of the devices. Fourth Avenue presents characteristics that differ from the remainder of the sites: low traffic volume and large trees all the way down the road which reduce the forward visibility and the perceived road width.

The model validity assessment, based on a relationship derived from validation site data (Fourth Avenue and Gale Lane), indicated that the differences found between this relationship and the calibrated speed profile model are generally under 3 km/h. This difference can be considered acceptable given that the relationships were derived from different data sets.

The speed profile model developed based on speed-distance data has effectively achieved the objective of predicting speeds for a given combination of traffic calming measures (with the notable exception of chicanes) implemented in sequence as demonstrated through the model validation process.

CHAPTER 9

CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER WORK

This chapter summarises the findings of this research which have been divided into two main parts concerning (a) the hypothesis testing and (b) the speed profile model. In addition new elements, which would have improved the speed profile model, have been introduced in this chapter based on the experiences acquired during the model development process. Recommendations have been presented based on these elements. Some advice on the application of the model is also provided. Finally suggestions for further research are introduced bearing in mind the need to improve the speed profile model and also to widen knowledge in this specific subject.

9.1 Main Findings from the Hypothesis Testing

The issues summarised here are the main findings from the data analysis related to the calibration site data conducted in chapter 6 apart from the last part of this section which refers to the findings of the downstream speed analysis presented in Appendix A. However, it should be noted that comments on results obtained from the validation site data (Chapter 8) have also been included in some of the analyses.

9.1.1 Consistency of Crossing Speeds

Speed cushions have shown similar effects on speeds at the devices whereas the same was not verified for the two chicanes at Livingstone Street. The inclusion of the validation sites allowed a more comprehensive analysis. Speed cushions presented consistent impacts apart from the cushion at Fourth Avenue whose dimensions differ from the remainder of sites. As noted by Layfield (1994) the overall width of the cushion is generally a good determinant of mean speeds; the cushion in Fourth Avenue presents the greatest overall width. Tables and humps present the same dimensions, nevertheless the equivalence of their impacts on speeds could not be accepted by the t-tests. This may be attributed to variations between sites particularly in input speeds as the speed differential between before and after speed measurements has been maintained for Fourth Avenue and Foxwood Lane (Layfield, unpublished). Chicanes presented a more unpredictable effect, with some having little impact on speeds, and the inconsistencies of their impacts may be attributed to the variations of dimensions and layout.

9.1.2 Additive Effect of Subsequent Measures

Cushions in sequence in Foxwood Lane East and in Gale Lane have shown similar speeds, indicating the absence of an additive effect. Chicanes in Livingstone Street could rather have suggested the opposite effect as the second chicane allows higher crossing speeds. With regard to different measures in sequence, average speeds at the measures in Fourth Avenue show increasing values as the link is crossed. Nevertheless, measures in Foxwood Lane West could have suggested the existence of an additive effect as the table presented a lower average speed than the hump, but it seems evident that the impact of the table on speeds is stronger than the hump. Overall there is no clear evidence that measures implemented in sequence cause an additive effect on speeds.

9.1.3 Effects of Input Speed

Linear relationships established between the input (entry) speed and the speed at the first calming measure were used to determine whether drivers exhibiting different behaviour respond in different ways to the measures. The relationships demonstrated a certain uniform response indicating similar behaviour irrespective of the input speed, in other words, for a given input speed there is a corresponding speed at the measure determined by the linear relationship. However, a degree of variability was detected, therefore indicating that although there is a certain pattern of behaviour, some drivers do not follow that pattern responding in different ways to the measures.

The effect of the input speed upon the effectiveness of the measures was analysed by linear relationships between the input speed and the speed at the measures in each link. Maximum speeds between measures were assumed as the input speed. There is a certain degree of explanation for the speed reduction effect of the measures especially for cushions as attested by the high R^2 values (Table 6.7), but low R^2 were found in the relationships established for the speed at the hump and at the table. The effect of the input speed upon the effectiveness of the measure can also be visually observed in individual speed profile plots which attest that the higher the entry speed ranges, the less effective the measures become as the measures are also crossed at higher speeds.

9.1.4 Factors Affecting Maximum and Minimum Speeds

The variables affecting maximum and minimum speeds were identified also through linear relationships. Although it is difficult to identify the factors affecting speeds, it appears that (a) the speed at the device is mainly affected by the type (geometry) of the device, while the distance from the previous measure and the maximum speed play a secondary role; (b) maximum speed is affected by a combination of the speed at which the upstream measure is crossed and the distance between measures.

The examination of the effect of different types of measures on speeds at the measures pointed out differences in impacts by type of measure. Table accounted for the highest impact on speeds, followed by hump, chicane and cushions in this descending order of impact. These differences in impacts were also found for validation site measures with the exception of chicanes which showed little impact on speeds. Layfield (1994) also found the same order of impact for table, humps and cushions. An indication of the relative impact of the different measures is given through the coefficients for the dummy variables in the speed profile model.

The study of acceleration/deceleration rates based on data from the calibration sites pointed out the likely point to attain maximum speed between measures. This point was determined through the interpolation of distance values in the average acceleration profile graphs plotted for each site. The position at which maximum speed was attained lies between 55 and 64% of the separation between measures in the direction of travel which is consistent with the findings of Baguley (1981).

The measure itself was determined as the point at which minimum speeds are normally achieved. This was the usual trend at the calibration sites, and the percentage of drivers achieving minimum speeds one data point before or one after the measures was very small.

9.1.5 Effects of the Type of Measure on Acceleration/Deceleration

The analysis of acceleration rates by type of measure conducted for the calibration sites showed different rates according to the type of measure. Speed cushions in Foxwood Lane East presented similar accelerations (0.24 to 0.29 m/s^2) and decelerations (around 0.33 m/s^2). The table and the hump presented the highest decelerations (0.74 and 0.82 m/s^2 respectively) and accelerations of 0.53 and 0.34 m/s^2 respectively. The chicanes presented deceleration (0.29 to 0.35 m/s^2) similar to the range observed for cushions, while the acceleration (0.50 m/s^2) is similar to the hump.

9.1.6 Effects on Overall Travel Time

Two approaches were used in the assessment of travel times at the calibration sites: total travel time and travel time by type of measure. Total travel time was determined by means of a linear relationship established between the entry speed and the total travel time in each surveyed link. The relationships present a reasonable R^2 value, and similar coefficients. However, their applicability is restricted to similar traffic calming schemes as they were developed for each site individually.

In order to extend the assessment of travel times and to provide a parameter to compare total travel times and delays by type of measure, two dimensions were used (i) space mean speed and (ii) slowness. The comparison of total travel time within sites indicated that the Foxwood Lane West scheme imposes the greatest delay (the highest slowness). The disaggregated analysis of travel time by the type of measure provided a contribution to the prediction of the required average travel time to negotiate the measures under consideration. Hence, for a given distance, travel time can be estimated based on the space mean speed obtained to travel the deceleration and acceleration lengths surrounding the surveyed measures. Considering individual measures, and using the space mean speed achieved for each type as a comparison element, the table constrains speeds to a lower level imposing the greatest delay, followed by the hump, chicanes and cushions, in descending order of impact.

9.1.7 Downstream Speed Analysis

This analysis has been conducted in order to investigate whether there would be an increase in speeds at a point downstream of a traffic calmed area as a result of recovering the time loss experienced while travelling at calmed areas. This analysis is fully presented in Appendix A. The comparison of the before and the after situation at the surveyed sites does not suggest such an effect as the means from four out of the six traffic streams are equivalent. In fact, Thanet Road and Askham Lane (from Gale Lane and Askham Lane respectively) suggest the opposite reaction since after mean speeds are lower than the before mean speeds. The result in Askham Lane is fully explained by the implementation of the roundabout which has changed the priority rule for vehicles coming ahead into Askham Lane. The results have shown no evidence of drivers speeding up after travelling through a calmed area. This is an important result which attests that traffic calming effects are not dissipated downstream, therefore no accident migration effect is likely to accur. However, it may be appropriate to confirm this result through further surveys in other locations.

9.2 Main Findings from the Speed Profile Model

The development of the speed profile model was based on data collected at three traffic calmed links. A speed-distance relationship was the basis for the model in addition to other known variables such as the type and the location of the calming measures. Simplifications and assumptions were inevitable during the calibration process in order to generate a simple model. In particular, equal impacts were assigned to all measures of a given type and the entry speed (V1) was taken as indicative of free flow speed.

The recommended speed profile model developed with a weighted least squares regression, which has the capability of explaining approximately 55% of the phenomenon 'speed', is:

$$Speed = -8.73 + 0.62V1 + 0.23dt + 0.78df - 0.0012dt^2 - 0.0137df^2 + 8.5E\text{-}05df^3 - 4.48H - 6.71T - 0.86C - 2.01Ch$$

where: $V1$ = input speed (in km/h)

dt = distance to the next measure (in metres)

df = distance from the previous measure (in metres)

H = if a hump is present

T = if a table is present

C = if a cushion is present

Ch = if a chicane is present.

The model presented a reasonable predictive capability for the calibration sites as graphically attested. The superimposition of modelled curves on observed profiles revealed that the modelled curves could have been any of the random observations in view of their similarity to the observed curves. Nevertheless, some discrepancies were found mainly related to the accuracy of the entry speed prediction outside a specified input speed range. Although all drivers did not attain maximum speed at the same data point, the predicted profile tended to underestimate distance to this point. These differences became even more noticeable in the acceleration profiles derived from the application of the speed profile model.

The speed profile model was the starting point to generate acceleration profiles at calming measures. The use of the difference quotient $\Delta v/\Delta x$ was preferred to using the first derivative of speed with respect to distance which would have resulted in an unwieldy expression. In this respect the acceleration profile also proved a reasonable prediction tool. It should be stressed that it will reproduce discrepancies encountered in the speed profile model as it was generated from the latter. The general form of the acceleration profile is:

$$\textit{acceleration} = \textit{Speed}\,(\Delta v/\Delta x)$$

The model validation process has assessed whether it represents (a) the other half of the calibration data and (b) the validation sites: Fourth Avenue, Gale Lane and Townend Street. The model fits the validation data from the calibration sites, Livingstone Street and Foxwood Lane East, well. It fits Fourth Avenue and Gale Lane quite well, but it does not fit Townend Street largely because the chicanes there have no effect on speeds. The model response in terms of the entry speed range prediction presented discrepancies at all sites. The optimum prediction proved to be restricted to certain speed ranges and outside those ranges entry speeds were overestimated for lower input speeds and underestimated for higher input speeds. A possible solution to this issue is dealt with in section 9.4. In general the model has demonstrated its suitability for the validation sites except for Townend Street, hence indicating that chicanes cannot reliably be included in the model due to their wide design variation. The sample of chicanes used in this study demonstrated diverse speed reduction levels, therefore making the model prediction unrealistic for chicanes whose impact differ from those included in the calibration process.

In summary, the speed profile model has effectively achieved the objective of predicting speeds of unimpeded cars and vans for a given combination of traffic calming measures, with the notable exception of chicanes, implemented in sequence in urban roads.

This output differs from previous studies on the prediction of speeds due to calming measures in that those studies have mostly focused on the prediction of (a) maximum speed as a function of distance between devices - flat and round topped humps (Lines, 1993 and Webster, 1993); (b) speed as a function of the device height (Mak, 1986); (c) speed change at the device and possibly upstream of it (Engel and Thomsen, 1992), rather than considering the effect on speeds of different measures implemented in sequence, therefore making comparisons between studies rather difficult.

9.3 Advice on the Application of the Model

Firstly, due to the lengthy model expression, it is recommended to use a spreadsheet to build the database matrix in order to calculate speeds at any desired data point. For instance, Excel 5.0 enables any alteration to the database matrix to be simultaneously amended in the formulae and also in the graphs embedded in the spreadsheet. This allows the assessment of various combinations of measures and spacing by a simple substitution of values. This approach should readily indicate the design most likely to achieve predetermined objectives.

In order to achieve more realistic predictions it is desirable to restrict the type of measures to those considered in the development of the model. As previously mentioned, chicanes are a delicate issue and the model represents the impact of a chicane which has similar design to the first one in Livingstone Street. Further work is needed to improve the effectiveness of chicanes, and hence to predict their impacts more reliably. The prediction of maximum speeds between measures is one of the main interests when planning a scheme. Therefore, in order to have a clear picture, it is also recommended to calculate model output for various data points which cover the likely length expected to contain the maximum speed (around 50 to 64% of the spacing).

9.4 Recommendations

The ideas presented in this section aim at improving the current research by reducing some of the restrictions of the developed model. They would represent a natural continuation of this research and could be undertaken without the need for a new data set although some adjustments would be required to the actual database.

Through the model validation and the sensitivity analysis it appears that the speed profile model predicts better when the input speed fed into the equation is close to the average value. The presentation of the individual speed profiles (for the calibration sites in Chapter 5) suggested distinct behaviour according to the entry speed. In order to better reproduce that speed variability, it would be reasonable to devise specific models in accordance to certain entry speed ranges so that there would be distinct models for lower, medium and high entry speeds by dividing the original database into three according to the actual entry speed. This process would minimise the entry speed underestimation and overestimation and would probably result in different predictions for different types of driving behaviour.

It was proved that different types of measures produced distinct impacts on speed. It may be that the impact of the type of the calming measure is better described by including the distance to that measure as a contribution to the explanation of its impact. This can be done by assigning to each type of measure a distinct variable describing the distance to and the distance from that measure. In practice this represents a multiplicative variable (the dummy variable for the type of measure multiplied by the variables distance to and distance from it) that weights differently the relative distance in accordance to the type of measure. In view of this, there would be as many 'distance to' and 'distance from' variables as the number of types of calming measure.

Differences in average speed at the measures of the same type (e.g. hump and table) which were also observed before the implementation of the calming schemes, raise the issue of these differences being attributed to the site. The type of road may be of some importance to the model as it may control speeds within certain levels. The before speed at the site may be used to characterise the site and act as an explanatory variable for 'speed'. Alternatively the type of road can be described by dummy variables (e.g. arterial, secondary, residential).

A mathematical approach could also be considered in the speed profile modelling process. The sine function was tested in an experimental basis and it has indicated the possibility of fitting the data into such a function (only average speeds were tested). A segmented model, which would consider the link divided into segments and each segment governed by a separate equation, would be more appropriate as the spacings between devices are not constant. However, early tests demonstrated problems of discontinuity in speed estimates. This approach is similar to those involving the development of acceleration-time relationships conducted by Lay (1987).

9.5 Suggestions for Further Work

Contrasting with the previous section, the following ideas cannot be tackled without introducing new data.

In spite of the detailed way of collecting data - using 16 channels simultaneously to provide a detailed speed profile - it has been limited to speed and distance data. The observation of drivers' behaviour while carrying out the fieldwork has indicated typical attitudes especially related to the age of the driver. For instance, young drivers tend to travel at higher speeds and elderly drivers at lower speeds. In view of this, it is reasonable to include other variables which may better explain drivers' behaviour such as the age and gender of the driver and the type of the car. However, it may be a difficult task to describe the type of the car, as one make has various models that present different engine power. The engine power may also influence the choice of travel speed especially if combined with driver characteristics (e.g. age, gender).

The addition of such variables would certainly contribute to improve the model capability of explaining the phenomenon 'speed' and it is likely to increase the correlation coefficient. However, while the inclusion of such variables represents a sophistication to the model, it is also a drawback in its application since it would demand more variables to achieve any speed prediction, hence restricting the applicability of the model.

The difference in the impact of chicanes on speeds has raised the attention for more in-depth analysis of their design. This study has produced evidence that some chicanes are totally ineffective in reducing speeds. However the results of off-road trials conducted by Sayer and Parry (1994) should be analysed with care as they may not reproduce the on-road situation. Consequently, this issue still requires further study to represent the vehicle speeds on public roads. Clearly some chicanes are ineffective as proved by the data collected. More detailed testing is needed to understand what contributes to effective design. Driving simulators have successfully been used to assess speed reducing measures, but this technique is not able to cope with vertical shifts to the carriageway. Nevertheless, the assessment of horizontal shifts, e.g. chicanes, could easily be undertaken. The validity of a driving simulator for this task could be assessed against the results achieved in this research and it could be extended to other chicanes comprising different designs in order to expand the knowledge of their impacts.

9.6 Final Remarks

The formulation of the speed profile model overcomes in part the lack of information on the relative impact of different traffic calming measures in different combinations. The knowledge of the impacts of speed cushions, humps, tables and chicanes considered in sequence is a valuable contribution to tackling the problems of achieving predetermined objectives using a range of measures. In addition to this engineering approach it may also contribute to an economic assessment such as social cost-benefit analysis to determine whether the investments will be worth the gains in safety.

The initial objective of this research has been achieved as the model reasonably predicts speeds of unimpeded cars and vans over a given combination of traffic calming measures (except chicanes) in sequence. While the model building process has involved simplifications and assumptions inevitable in the analysis of speeds on traffic calmed roads, the model captures the essence of the phenomenon 'speed'. It is a simplification of the phenomenon as it represents all the observed variability in drivers' behaviour in a single relationship.

REFERENCES

ABBOTT, P.G., PHILLIPS, S.M. and LAYFIELD, R.E. (1995). *Vehicle and Traffic Noise Surveys Alongside Speed Control Cushions in York.* TRL, Project Report **103**, Crowthorne.

ADAMS, J. (1985). *Risk and Freedom: The record of rod safety regulation.* Transport Publishing Projects. London.

AKCELIK, R., BIGGS, D.C., and LAY, M.G. (1983). Modelling Acelleration Profiles. *Australian Road Research Board,* Internal Report **AIR-390-9**.

AKCELIK, R., BIGGS, D.C. (1987). Acceleration Profile Models for Vehicles in Road Traffic. *Transportation Science,* vol 21(1): 36-54, February.

ANDERSON, D.R., SWEENEY, D.J. and WILLIAMS, T.A. (1990). *Statistics for Business and Economics.* West Publishing Company, Saint Paul, USA.

APPLEYARD, D. (1981). *Liveable Streets.* University of California Press, Berkeley.

BAGULEY, C. (1981). *Speed humps-further public road trials.* TRRL, Report **LR 1017**, Crowthorne.

BENNETT, G.T. (1983). Speeds in Residential Areas. *The Highway Engineer*, vol 30(7): 2-5.

BIGGS, D.C., AKCELIK, R. (1985). Further Work on Modelling Car Fuel Consumption. *Australian Road Research Board,* Internal Report **AIR-390-10**.

BONSALL, P (1992). *Speed, Delay and Congestion Surveys.* Notes from MsC Course. Institute for Transport Studies, University of Leeds.

BOWERS, P. H. (1986). Environmental Traffic Restraint: German Approaches to Traffic Management by Design. *Built Environment* vol 12(1/2): 60-73.

BOX, P.C., OPPENLANDER, J.C. (1976). *Manual of Traffic Engineering Studies.* Institute of Transportation Engineers, Fourth edition.

BRINDLE, R.E. (1992). Australia's Contribution to Traffic Calming. *PTRC,* Seminar G: 49-60.

BROADBENT, K., SALMON, A.M. (1991). An Experiment with Road Humps. *Highways and Transportation* vol 38(11): 5-8.

BROADBENT, K., SALMON, A.M. (1993). An Alternative to Road Humps. *Highways and Transportation* August: 6-9.

CAIRNEY, P.T., FACKRELL, H.L. (1993). The Effects of a 40 km/h Local Area Speed Limit on Traffic Behaviour and Community Perceptions and Opinions. *Australian Road Research Board.* Research Report **ARR 243**, July.

COLLINS, M.S.(1990). Traffic Calming and Environmental Management. *PTRC,* Seminar B: 25-35.

CSS, DoT, AMDE, ALBES and ACTO (1994). *Traffic Calming in Practice.* Landor Publlishing, London.

CYNECKI, M.J., SPARKS, J.W., and GROTE, J.L. (1993). Rumble Strips and Pedestrian Safety. *ITE Journal,* August: 18-24.

DEPARTMENT OF TRANSPORT/INSTITUTION OF HIGHWAYS AND TRANSPORTATION (1987). *Roads and Traffic in Urban Areas.* HMSO, London.

DEPARTMENT OF TRANSPORT, (1991). *Traffic Appraisal Manual.*

DEPARTMENT OF TRANSPORT, (1991a). *20MPH Speed Limit Zones.* Traffic Advisory Leaflet 7/91, May.

DEPARTMENT OF TRANSPORT, (1993). *Traffic Calming Regulations.* Traffic Advisory Leaflet 7/93, August.

DEPARTMENT OF TRANSPORT, (1994). *Entry Treatments.* Traffic Advisory Leaflet 2/94, August.

DEVON COUNTY COUNCIL (1991). *Traffic Calming Guidelines.* Devon County Council Engineering and Planning Department.

DOLDISSEN, A. (1988). Environmental Traffic Management. German Interministerial Programme. *PTRC* Seminar M: 71-85.

DOLDISSEN, A., DRAEGER, W. (1990). Environmental Traffic Management Strategies in Buxtehude, West Germany. in Tolley, *The greening of urban transport.*

DONALD, D. (1994). Reducing Speed. The Relative Effectiveness of a Variety of Sign Types. *Australian Road Research Board.* Research Report **ARR 246**, January.

DURKIN, M., PHEBY, T. (1992). York: Aiming to Be the UK's First Traffic Calmed City. *PTRC*, Seminar G: 73-90.

ELLIS-KING, G. (1993). Traffic Calming as a Focus for Wider Environmental Improvements. Paper presented at *Traffic Calming Conference* in York, September: 1-3.

ENGEL, U., THOMSEN, L. (1992). Safety Effects of Speed Reducing Measures in Danish Residential Areas. *Accident Analysis & Prevention,* vol 24(1): 17-28.

ESPIÉ, S., LENOIR, F. (1991). The Future of Road Traffic Measurement. *Recherche Transports Sécurité,* English issue, N.6, Février.

GERLOUGH, D.L.,HUBER,M.J. (1975). Traffic Flow Theory. *Transportation Research Board*, Special Report 165.

GUJARATI, D.N. (1988). *Basic Econometrics.* McGraw-Hill Book Company.

HARRISON, I.B. (1992). Development of Traffic Calming in Devon. *PTRC,* Seminar G: 91-104.

HARVEY, T. (1992). *A Review of Current Traffic Calming Techniques.* DRIVE project V2016/31101.

HASS-KLAU, C. (1986). Environmental Traffic Management in Britain - Does it Exist? *Built Environment* vol 12(1/2): 7-19.

HASS-KLAU, C. (1986a). Environmental Traffic Management: Pedestrianisation and Traffic Restraint - a contribution to road safety. *PTRC* Seminar M: 137-150.

HASS-KLAU, C. (1990). *The Pedestrian and City Traffic.* London, Belhaven Press.

HASS-KLAU, C. (1990a). *An Illustrated Guide to Traffic Calming.* Friends of the Earth, London.

HASS-KLAU, C., NOLD, I., BOCKER, G and CRAMPTON, G. (1992). *Civilised Streets: a guide to traffic calming.* Environmental & Transport Planning, Brighton.

HASS-KLAU, C. (1993). Impact of Pedestrianization and Traffic Calming on Retailing.*Transport policy,* vol 1(1): 21-31.

HASS-KLAU, C., NOLD, I. (1993). State of the Art Assessment of Road Humps and Their Relationship to Traffic Calming. *PTRC,* Seminar A: 205-214.

HEWITT, R.H., CHAMBERS, J.B. and WHITE, A.N. (1974). Graphical Solution of Moving Observer Surveys. *The Highway Engineer.* June, 12-17.

HIDDAS, P. (1993). Speed Management in Local Streets: A Continuous Physical Control Technique. *Road & Transport research,* vol 2(4): 18-27.

HOOBS, F.D. (1979). *Traffic Planning & Engineering*. Pergamon Press.

HODGE, A.R. (1992). A Review of the 20 Mile/h speed Zones: 1991. *Traffic Engineering & Control*, October: 545-547.

HODGE, A.R. (1993). *Speed Control Humps - A Trial at TRL.* TRL Project Report **32.** Crowthorne.

HOMBURGER, W.S., KEEFER, L.E., McGRATH, W.R. (1976). *Transportation and Traffic Engineering Handbook.* Institute of Transportation Engineers. Prentice-Hall. London.

JARVIS, J.R. (1987). Acceleration Lane Design. *Australian Road Research Board,* Internal Report **AIR 281-1**.

JARVIS, J.R., GIUMMARRA, G. (1992). Humps for the Use on Bus Routes. *Road & Transport Research* vol 1(4): 32-47.

JOHNSTON, I.R., FRASER, P.J. (1983). Do 'Visible' Vehicle Detectors Really Influence Driver Behaviour? *Australian Road Research Board*, Technical Note No 2, Vol 13(3), September.

JUST, U. (1992). Local Transport Strategies in North-Rhine Westphalia. in *Traffic Congestion: Is there a way out?* edited by John Whitelegg.

KELLER, H. H. (1986). Environmental Traffic Restraints on Major Roads in the Federal Republic of Germany. *Built Environment* vol 12(1/2): 44-59.

KENNEDY, N., KELL, J. H., HOMBURGER, W.S.(1973). *Fundamentals of Traffic Engineering*. Institute of Transportation and Traffic Engineering, University of California, Berkeley.

KLIK, M., FAGHIRI A.(1993). A Comparative Evaluation of Speed Humps and Deviations. *Transportation Quarterly* vol 47(3): 457-469.

KRAAY, J. H. (1986). Woonerven and the Experiments in Netherlands. *Built Environment* vol 12(1/2): 20-29.

KRAUSE, J. (1986). Experiences, Problems and Strategies with Area-wide Verkehrsberuhigung in Germany - Six Demonstration Projects. *PTRC,* Seminar P: 105-116.

LAY, M.G. (1987). Acceleration-Time Relationships. *Australian Road Research Board,* Internal Report **AIR 454-2**, November.

LAY, M.G. (1990). *Handbook of Road Technology.* Volume 2, Traffic and Transport, Gordon and Breach Science Publishers, London.

LAYFIELD, R.E. (1994). The effectiveness of Speed Cushions as Traffic Calming Devices. *PTRC,* Seminar G: 29-40.

LAYFIELD, R.E., HODGE, A.R., and PARRY, D.I. (unpublished). *On-road Trials of Speed Cushions in Sheffield and York.* TRL Project Report PR/TT/030/94.

LINES, C.J.(1993). Road Humps for the control of vehicle speeds. *Traffic Engineering and Control*, January: 2-7.

MACKIE, A. M., WARD, H. and WALKER, R. T. (1990). *Urban Safety Project: 3. Overall evaluation of area wide schemes.* TRRL, Research Report **RRL 263**, Crowthorne.

MAK, K.K. (1986). A Further Note on Undulation as a Speed Control Device. *Transportation Research Record*, 1069: 13-20.

MAY, A.D., BONSALL, P.W., and MARLER, N.W. (1989). Car Travel Time variability on links of a radial route in London: methodology, surveys and data processing. Working Paper 278, *Institute for Transport Studies*, University of Leeds.

McCLUSKEY, J.(1992). *Roadform & Townscape*. The Architectural Press.

McDONALD, P. (1983). The Use of Road Humps in the Residential Streets in the Shire of Corio. Local Street Traffic and Safety Workshop Papers and Discussions. *Australian Road Research Board*, Research Report **AAR 129**, August.

McNAMARA, K. (1983). City of Hawthorn Road Humps. Local Street Traffic and Safety Workshop Papers and Discussions. *Australian Road Research Board*, Research Report **AAR 129**, August.

McSHANE, W.R, ROESS, R.P. (1990). *Traffic Engineering*. Prentice Hall, Englewood Cliffs, New Jersey.

METCALFE, A.W. (1994). *Statistics in Engineering. A practical approach.* Chapman & Hall. London.

MONHEIM, H. (1986). Area-wide Traffic Restraint: A Concept for Better Urban Transport. *Built Environment* vol 12(1/2): 74-82.

MONHEIM, R. (1986). Pedestrianization in German Towns: A process of continual development. *Built Environment* vol 12(1/2): 30-43.

MONHEIM, R. (1990). The Evolution and Impact of Pedestrian Areas in the Federal Republic of Germany. in Tolley, *The Greening of Urban Transport.*

NIELSEN, O.H., RASSEN, J. (1986). Environmental Traffic Management in Odense, Denmark. *Built Environment* vol 12(1/2): 83-97.

PAPACOSTAS, C.S. (1987). *Fundamentals of Transportation Engineering.* Prentice-Hall, INC., New Jersey.

PHAROAH, T., RUSSELL, J.(1989). *Traffic Calming: Policy and Evaluations in Three European Countries.* Occasional paper, South Bank Polytechnic.

PHAROAH, T.(1992). *Less Traffic, Better Towns.* Friends of the Earth, London.

PYNE, H.C., CARSTEN, O.M.J., and TIGHT, M.R (1995). Speed on Rural Arterial Roads. *Conference on Road Safety in Europe & Strategic Highway Research Programme,* VTI Rapport, 2A, part 4: 7-22.

PITCHER, I.K. (1989). Driver Perception of a Series of On-Road Treadle Sensors. *Australian Road Research Board.* Technical Note No 3, Vol 19(2), June.

PITCHER, I.K. (1989a). Speed Profiles of Isolated Vehicles in Residential Streets. *Australian Road Research Board.* Research Report **ARR 166**, December.

RIEMERSMA, J.B.J., van der HORST, A.R.A, HOEKSTRA, W., ALINK, G.N.M. and OTTEN, N. (1990). The Validity of a Driving Simulator in Evaluating Speed-reducing Measures. *Traffic Engineering & Control*, July/August, 416-420.

RUSSELL, J.R.E. (1988). Traffic Integration and Environmental Traffic Management in Denmark. *Transport Rewiews* vol 8(1): 39-58.

SAMUELS, S.E. (1976). Acceleration and Deceleration of Modern Vehicles. *Australian Road Research,* vol 6(2): 23-28, June.

SAYER, I.A., PARRY, D.I. (1994). *Speed Control Using Chicanes - A Trial at TRL.* TRL Project Report **102**, Crowthorne.

SCHLABBACH, K. (1991). Traffic Calming and Urban Development Policy. *PTRC,* Seminar A: 129-134.

SCHLEICHER-JESTER, F.(1989). Tempo 30 In Towns - Results of a German Experiment. *PTRC,* Seminar H: 227-287.

SECO, A.J.M. (1991). *Driver Behaviour at Uncontrolled Junctions.* PhD Thesis, Department of Civil Engineering, ITS, University of Leeds.

SUMNER, R., BAGULEY, C. (1979). *Speed Control Humps on Residential Roads.* TRRL, Report **878**, Crowthorne.

TAN, H.W., WARD, B.J. (1993). The Effectiveness of 90° Bends in Controlling Speed on Urban Local Roads. *Australian Road Research Board.* Research Report **AAR 247**, September.

TAYLOR, M.A.P. (1983). Vehicle Speeds on Residential Streets. *Australian Road Research Board,* Research Report **AAR 129**, Suplementary Paper, August: 13-20.

TAYLOR, M.A.P. (1984). Design Aids for Local Area Traffic Management. *Civil Engineering Transactions,* The Institution of Engineers, Australia, vol 26: 254-263.

TAYLOR, M.A.P., RUTHERFORD, L.M. (1986). Speed Profiles at Slow Points on Residential Streets. Civil Engineering Working Paper 86/4, *Monash University*, Dept. of Civil Engineering, Victoria.

TAYLOR, M.A.P. (1986). Controlling Vehicle Speeds on Local Streets. Technical Note No 1, *Australian Road Research*, 16(1): 42-44.

TAYLOR, M.A.P., YOUNG, W. (1988). *Traffic Analysis. New Technology & New Solutions*. Hargreen Publising Company. Melbourne.

TEST (1989). *Quality Streets*. Transport and Environment Studies, London.

TOLLEY, R. (1990). *Calming Traffic in Residential Areas*. Brefi, Tregaron.

TRANSPORT RESEARCH LABORATORY (1993). *Urban Road Traffic Surveys*. Overseas Road Note 11, Crowthorne.

VIS, A.A., DIJKSTRA, A., and SLOP, M. (1992). Safety Effects of 30 km/h Zones in The Netherlands. *Accident Analysis and Prevention*, vol 24(1): 75-86.

WARD, H., ALLSOP, R. (1982). Area-wide Approach to Urban Road Safety - Evaluation of Schemes by Monitoring of Traffic and Accidents. *Traffic Engineering & Control*, Sept, 424-428.

WATTS, G.R. (1973). *Road Humps for the Control of Vehicle Speeds*. TRRL Report **LR 597**, Crowthorne.

WATTS, G.R. (1978). *Results from Three Trial Installations of Rumble Areas*. TRRL Report **SR 292**, Crowthorne.

WEBSTER, D.C. (1993). *Road Humps for Controlling Vehicle Speeds*. TRL Project Report **18**, Crowthorne.

WEBSTER, D.C. (1993). The Grounding of Vehicles on Road Humps. *Traffic Engineering and Control*, July/August: 369-371.

WEBSTER, D.C., LAYFIELD, R.E. (1993). *An Assessment of Rumble Strips and Rumble Areas.* TRL Project Report **33**, Crowthorne.

WEBSTER, D.C. (1994). *Speed at 'Thumps' and Low Height Road Humps.* TRL. Project Report **101**, Crowthorne.

WHEELER, A.H (1992). *Resume of Traffic Calming Schemes on Main Roads Through Villages.* TRRL, Working Paper WP/TS/61, Crowthorne.

WHEELER, A.H., TAYLOR, M., PAYNE, A. (1993). *The Effectiveness of Village 'Gateways' in Devon and Gloucestershire.* TRL, Project Report **35**, Crowthorne.

WINDLE, R., MACKIE, A.M. (1992). *Survey on Public Acceptability of Traffic Calming Schemes.* TRRL, Contractor Report 298, Crowthorne.

WIT, T. (1984). Traffic Hump as Recommended by SVT: Design and Effects. *PTRC.* Seminar L: 101-109.

ZAIDEL, D., HAKKERT, S., BARKAN, R. (1984). An Experimental Comparison of Paint Stripes & Rumble Strips at Low Volume Rural Intersection. *PTRC.* Seminar L: 41-54.

APPENDIX A

DOWNSTREAM SPEED ANALYSIS

This section deals with the investigation of hypothesis *m) whether drivers speed up after travelling through a calmed link in order to recover any time loss.* This analysis is based on a special set of data not used so far. As explained in Chapter 4 (section 4.12) the data sets refer to spot speed data collected at three sites namely Thanet Road, Askham Lane and Front Street, before and after the implementation of traffic calming schemes. A complete description of the sites is also provided in section 4.12.

Speeds were measured downstream of traffic calmed areas using a radar speed meter. It should be noted that the speed unit used throughout this analysis is miles per hour (mph) since the radar gun was calibrated for readings of speed in such a unit.

A.1 Sample Size

The data collection timetable has been presented in Chapter 4 (Table 4.8). The Thanet Road sample does not include the first two data collection days (in July) in order to be more consistent with the other sites. By omitting these, the data becomes more homogeneous in terms of (a) the period of the year, (b) the method of data collection in terms of the number of observers, and (c) the number of data collection days.

With respect to the after data collection period for Askham Lane, it was decided to disregard the first day as speed measurements were taken at a point too close to the junction underestimating speeds as a result. This was corrected on the following day guided by pictures previously taken to record the field work (before the implementation of the calming measures). The overall sample for each station is shown in Table A.1 below.

Table A.1: Sample size at each spot speed survey station

STATIONS	TRAFFIC STREAM FROM	SAMPLE SIZE	
		BEFORE	AFTER
THANET ROAD	Gale Lane	528	403
	Foxwood Lane	148	139
FRONT STREET	Askham Lane	415	274
	Gale Lane	398	299
ASKHAM LANE	Askham Lane	349	170
	Foxwood Lane	82	103

The changes on these three stations between before and after periods refer to:

a) traffic calming in Gale Lane;

b) traffic calming in Askham Lane with the construction of a roundabout at Askham Lane/Foxwood Lane; and

c) completion of the traffic calming scheme in Foxwood Lane from Bellhouse Way to the junction with Askham Lane.

As can be seen in Table A.1, data have been aggregated according to the station and the origin. This has been possible since speed distributions within days are roughly comparable as shown by the average speed, variance and standard deviation in Table A.2 provided for each day and each origin and also through the examination of cumulative frequency curves for each day (these curves have not been presented). The cumulative frequency curves were checked because, for a given site and origin, the mean speeds were not equivalent. For instance, the mean for the first day was equivalent to the mean of the second day; the second day to the third one; the third to the fourth one, but the first day was not equivalent to the third day. In cases like this, the plot of superimposed frequency curves would disclose any significant difference in the distribution of speeds within days.

Table A.2: *Before and after mean speeds, variance and standard deviation at each station (by day and origin)*

		THANET ROAD						FRONT STREET						ASKHAM LANE					
B		from Gale Lane			from Foxwood Lane			from Askham Lane			from Gale Lane			from Askham Lane			from Foxwood Lane		
E	Days	Mean	Var.	STD	Mean	Var.	STD	Mean	Var.	STD	Mean	Var.	STD	Mean	Var.	STD	Mean	Var.	STD
F	14/Oct/93	30.44	18.02	4.24	30.50	21.91	4.68	26.04	16.33	4.04	27.48	15.21	3.90	43.68	28.88	5.37	35.82	9.01	3.00
O	19/Oct/93	33.63	14.27	3.78	32.51	16.97	4.12	27.30	11.89	3.45	27.04	11.71	3.42	44.27	26.17	5.12	35.67	9.29	3.05
R	21/Oct/93	32.59	15.67	3.95	32.17	13.88	3.72	28.08	13.94	3.73	28.80	10.90	3.30	43.40	33.48	5.79	33.82	8.60	2.93
E	22/Oct/93	32.26	19.18	4.38	33.35	8.44	2.90	26.52	11.84	3.44	26.88	13.06	3.61	44.35	31.38	5.60	32.63	8.02	2.83
A																			
F	25/Oct/94	30.96	16.75	4.09	32.23	17.23	4.15	26.01	10.35	3.22	26.34	12.70	3.56	-	-	-	-	-	-
T	26/Oct/94	32.28	15.96	4.00	32.19	15.64	3.95	26.76	11.88	3.45	26.87	12.60	3.55	37.02	19.84	4.45	35.11	15.55	3.94
E	27/Oct/94	30.77	16.98	4.12	31.08	12.94	3.60	26.47	19.89	4.46	26.63	14.04	3.75	35.80	20.84	4.55	34.70	12.76	3.57
R	2/Nov/94	31.85	15.24	3.90	31.60	18.69	4.32	26.79	12.76	3.57	27.93	16.50	4.06	36.60	19.63	4.43	36.58	8.59	2.93

A.2 Data Analysis Methodology

At all three survey stations the traffic flow is composed of two distinct traffic streams. The before situation at Thanet Road required a special strategy to classify the two traffic streams as one of them referred to an already traffic calmed link. In like manner this strategy was applied to the remainder of sites in order to detect differences, if any, between traffic streams.

As a result of the data collection strategy, data have been analysed according to the following steps:

a) testing the difference between means of the two traffic streams for the before situation;

b) testing the difference between means of the two traffic streams for the after situation; and

c) testing whether there is any difference between means before and after for

   c.1) the first traffic stream; and

   c.2) the second traffic stream.

T-tests have been applied in the cases above where the null hypothesis asserts that means are equal as follows:

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 <> \mu_2$$

A.2.1 Thanet Road

Testing the difference between means (Gale Lane and Foxwood Lane)

According to Table A.3, there is no difference between means of these two traffic streams for either periods. It should be noted that, for the before period, vehicles coming from Foxwood Lane travelled through a calming area. The downstream mean speeds can be accepted as equal although the traffic conditions on Foxwood Lane were restrained by calming measures.

Table A.3: Thanet Road - difference between means

	Before			After	
	Gale Ln	Foxwood Ln		Gale Ln	Foxwood Ln
Mean	32.17	32.30		31.46	31.72
Variance	18.05	15.02		16.53	15.90
Observations	528	148		403	139
df	674			540	
t Stat	-0.349			-0.642	
t Critical	1.963			1.964	

Before and after comparisons

Table A.4 indicates differences for means related to traffic coming from Gale Lane. The after period mean is significantly smaller than the before mean at the 95% confidence level. Conversely, for Foxwood Lane there is no evidence on which to reject the equivalence of means, therefore indicating no changes in before/after mean speeds.

Table A.4: Thanet Road - before and after comparison among traffic streams

	From Gale Ln			From Foxwood Ln	
	Before	After		Before	After
Mean	32.17	31.46		32.30	31.72
Variance	18.05	16.53		15.02	15.90
Observations	528	403		148	139
df	883			283	
t Stat	2.570			1.258	
t Critical	1.963			1.964	

In order to give a perception of the traffic conditions at the Thanet Road station, Figure A.1 depicts the junction upstream of the station while Figure A.2 shows the site at which speeds were measured.

Figure A.1: Thanet Road towards Gale Lane and Foxwood Lane (on the left)

Figure A.2: Thanet Road Station - measurement point

A.2.2 Front Street

Testing the difference between means (Gale Lane and Askham Lane)

Table A.5 shows difference between means of these two traffic streams for the before period. These roads were calmed after the first survey period.

Table A.5: Front Street - difference between means

	Before			After	
	Gale Ln	Askham Ln		Gale Ln	Askham Ln
Mean	27.45	26.87		26.95	26.46
Variance	13.36	14.02		14.23	13.69
Observations	398	415		299	274
df	811			571	
t Stat	2.224			1.578	
t Critical	1.963			1.964	

Before and after comparisons

According to Table A.6 there is no difference in means when comparing before and after speed measurements, that is no changes in mean speeds were verified for traffic coming either from Gale Lane or from Askham Lane.

Table A.6: Front Street - before and after comparison among traffic streams

	From Gale Ln			From Askham Ln	
	Before	After		Before	After
Mean	27.45	26.95		26.87	26.46
Variance	13.36	14.23		14.02	13.69
Observations	398	299		415	274
df	631			687	
t Stat	1.752			1.430	
t Critical	1.964			1.963	

Figure A.3 shows the junction upstream of the station (towards Askham Lane) and Figure A.4 shows the site at which speeds were measured (Front Street).

Figure A.3: Front Street towards Askham Lane and Gale Lane (on the left)

Figure A.4: Front Street Station - speed measurement point corresponding to the red car

A.2.3 Askham Lane

Testing the difference between means (from Askham Lane and Foxwood Lane)

Differences between means found at this station, shown in Table A.7, are maintained for the before and after periods, that is mean speeds related to the traffic stream from Foxwood Lane and Askham Lane cannot be considered equal at the 95% confidence level. The final 350 m of Foxwood Lane, which leads to the junction with Askham Lane, was not calmed when the before period surveys were carried out.

Table A.7: Askham Lane - difference between means

	Before			After	
	Askham Ln	Foxwood Ln		Askham Ln	Foxwood Ln
Mean	43.96	34.49		36.51	33.88
Variance	30.06	10.13		20.07	17.93
Observations	349	82		170	103
df	210			225	
t Stat	-20.68			4.852	
t Critical	1.971			1.971	

Before and after comparisons

Comparing mean speed within sites (see Table A.8), Foxwood Lane shows no difference in mean speeds for the before and after periods, whereas the mean speed at Askham Lane does not at the 95% confidence level.

Table A.8: Askham Lane - before and after comparison among traffic streams

	From Foxwood Ln			From Askham Ln	
	Before	After		Before	After
Mean	34.49	33.88		43.96	36.51
Variance	10.13	17.93		30.06	20.07
Observations	82	103		349	170
df	183			517	
t Stat	1.073			15.391	
t Critical	1.973			1.965	

The after mean speed presents a lower value than the before one which is not surprisingly due to the implementation of a roundabout. Figures A.5 and A.6 depict the before and after situation at Askham Lane at the junction with Foxwood Lane.

Figure A.5: Askham Lane - before situation

Figure A.6: Askham Lane after the implementation of the traffic calming scheme

A.3 Conclusions

This study has been conducted in order to investigate whether there would be an increase in speeds at a point downstream of a traffic calmed area as a result of recovering the time loss experienced while travelling at calmed areas.

The results shown in the previous sections and summarised in Table A.9 do not suggest such an effect. The means from four out of the six traffic streams have shown no significant difference, while Thanet Road and Askham Lane (from Gale Lane and Askham Lane respectively) suggest the opposite reaction since after mean speeds are lower than the before mean speeds.

Table A.9: Summary of the comparison between before and after means

Stations	Traffic stream from	Before and after means	
		equivalent *	comparison
THANET ROAD	Gale Lane	no	$\mu_B > \mu_A$
	Foxwood Lane	yes	-
FRONT STREET	Askham Lane	yes	-
	Gale Lane	yes	-
ASKHAM LANE	Askham Lane	no	$\mu_B > \mu_A$
	Foxwood Lane	yes	-

* at the 95% confidence level

Askham Lane presents a peculiar situation. Before the installation of the calming schemes, vehicles travelling ahead into the Askham Lane survey station could develop high speeds, firstly because of the priority rules and secondly, because the road was unimpeded. The implementation of the calming schemes, especially the roundabout at the junction with Foxwood Lane imposed a new priority rule for vehicles travelling ahead, therefore forcing them to slow down in order to negotiate the roundabout. In view of this, it is natural to find lower mean speeds at the Askham Lane station from vehicles travelling ahead. The traffic conditions for Foxwood Lane did not change even though vehicles had to negotiate the roundabout, rather than a give-way junction.

These results do not confirm the initial hypothesis as they have shown no evidence of drivers speeding up after travelling through a traffic calming area.

It is likely that some characteristics of the surveyed stations such as, traffic flow rate, trap length, existence of turning left/right, street width, proximity of traffic lights, may have affected vehicles' speed so that any speed change due to traffic calming schemes could not be pin-pointed. It may be that this effect could be found elsewhere but this is beyond the resources of this research.

APPENDIX B

PREVIOUS REGRESSION MODELS

B.1 First Modelling Attempts

Models tested:

$$Y = a + bx + cx^2 \quad \text{(quadratic)}$$

$$Y = a + bx + cx^2 + dx^3 \quad \text{(cubic)}$$

$$Y^3 = a + bx + cx^2 \quad \text{(quadratic - cubic speed)}$$

$$Y^3 = a + bx + cx^2 + dx^3 \quad \text{(cubic - cubic speed)}$$

These models were applied to sections of the links as indicated in Tables B.1, B.2 and B.3, which present the R^2 values and the coefficients (a, b, c, d) obtained for the regression models.

Table B.1: R^2 and coefficients - Foxwood Lane East n=345

Model		0<x<66 m	0<x<22 m	22<x<66 m
quadratic	R^2	0.031	0.023	0.0584
	a	22.316	34.458	25.248
	b	-0.1415	-0.0667	0.200
	c	0.00274	-0.0033	-0.0009
cubic	R^2	0.035		
	a	32.69		
	b	-0.302	-	-
	c	0.0097		
	d	-7.2E-05		
quadratic (y^3)	R^2	0.019		0.033
	a	40272.1	-	24116.7
	b	-448.99		336.04
	c	8.392		-0.0977
cubic (y^3)	-	-	-	-

Table B.2: R^2 and coefficients - Foxwood Lane East (average speed)

Model		0<x<105m	22<x<105m	105<x<185m	22<x<66m	56<x<105m
cubic	**R^2**	0.926	0.993	0.9930	0.997	0.9999
	a	32.562	26.843	36.653	30.828	23.1222
	b	-0.252	0.064	-0.529	-0.2503	0.24119
	c	0.0078	0.0026	0.0066	0.0101	0
	d	-5.5E-05	-2.9E-05	-2.1E-05	-8.47E-05	-1.66E-05
quadratic	**R^2**		0.951	0.969	0.987	0.9989
	a		22.11	-25.1408	25.256	14.957
	b		0.364	0.7996	0.1996	0.5605
	c		-0.0027	-0.0027	-0.00093	-0.00404
	d					
quadratic (y^3)	**R^2**				0.986	1.0
	a				14295.44	-15698.93
	b				516.643	1625.26
	c				-1.787	-11.793
cubic (y^3)	**R^2**		0.989	0.9919	0.998	0.9993
	a		18058.2	57181.15	32417.9	8300.40
	b		163.039	-1787.47	-947.05	690.070
	c		8.386	21.0656	34.302	0
	d		-0.089	-0.0667	-0.2755	-0.0482

Table B.3: R^2 and coefficients - Foxwood Ln West n= 153

Model		36<x<103 m	36<x<79 m	70<x<103 m	0<x<36 m
quadratic	**R^2**				0.2167
	a				36.608
	b				0.00093
	c				-0.0077
cubic	**R^2**	0.175	0.115	0.2403	0.2167
	a	26.164	38.547	37.8855	36.5889
	b	-0.2969	-1.008	-0.6528	0.01832
	c	0.01163	0.02465	0.01508	-0.00912
	d	-8.7E-05	-0.00016	-9.8E-05	2.55E-05
cubic (y^3)	**R^2**				0.1449
	a			-	55452.91
	b	-	-		54.596
	c				-48.4096
	d				0.6174
quadratic (y^3)	-	-	-	-	-

B.2 Cricket Graphs - Curve Fit for Average Speeds

The 'Cricket Graphs' software was used for the curve fit of average speeds into polynomials of the fifth-order for Foxwood Lane West and East. The curve fit, the estimated coefficients of the regression equation and the correlation coefficient are presented next.

B.2.1 Foxwood Lane West

$$Y = 28.07 - 0.816x + 0.030\,x^2 - 0.00048x^3 + 0.000003x^4 - 0.00000001x^5$$

$$R^2 = 0.65$$

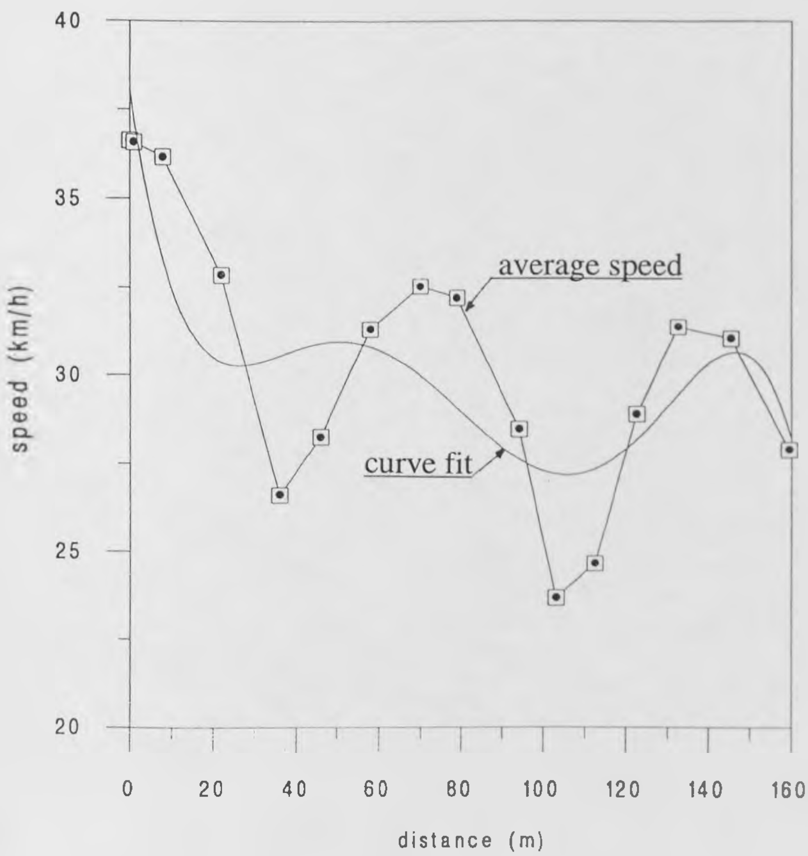


Figure B.1: Foxwood Lane West - Curve fit for average speed

B.2.2 Foxwood Lane East

$$Y = 33.05 - 0.432x + 0.019x^2 - 0.00029x^3 + 0.0000018x^4 - 0.000000004x^5$$

$$R^2 = 0.71$$

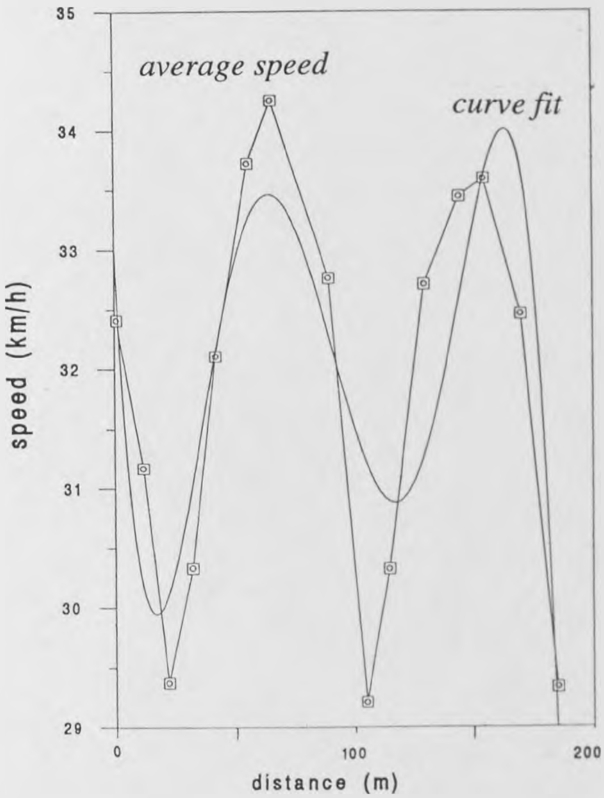


Figure B.2: Foxwood Lane East - curve fit for average speed

B.3 Modelling Attempts Using Transformed Distance Variables

This relative distance approach treats each measure individually and to each one is assigned a relative distance variable so that, for a given measure A (the first measure), the relative distance is represented by two variables: *da1* (from the origin to the measure) and *da2* (from the measure up to the end of the link). These relative distance variables were expressed by mathematical functions as described in section 7.2.2. In the following tables these variables were designated as:

da = inverse of the squared distance;

da + ln = logarithm function; and

da + sqr = square root function.

Table B.4: Summary for Foxwood Lane West n = 153 vehicles (downstream dummy variables)

MODEL	V1	d	d^2	d^3	$1/(d_a-d)^2$	Ln	Dummy H, T, C	R^2	not in the equation	fail t-test
2	x	x			x		x	0.611	C	
3	x	x	x		x		x	0.626	C	
4	x	x	x	x	x		x	0.627	C	d^2, d^3
6	x	x				x	x	0.631	C	dcln
7	x	x	x			x	x	0.634	C	
8	x	x	x	x		x	x	0.636	C	d^2
9	x	x					x	0.485	C	
10	x	x	x				x	0.520	C	
11	x	x	x	x			x	0.527	C	T

Table B.5: Summary for Foxwood Lane East n = 172 vehicles (half sample: odd vehicles) downstream dummy variables

MODEL	V1	d	d^2	d^3	$1/(d_a-d)^2$	Ln	Square root (sqr)	Dummy variables C1,C2,C3	R^2	not in the equation	fail t-test
2	x	x			x			x	0.539	C2	
3	x	x	x		x			x	0.539	C3	d^2
4	x	x	x	x	x			x	0.539	C3, d^2	d^3
16	x	x					x	x	0.548	C2	da1sqr
17	x	x	x				x	x	0.548	C3	d^2, da1sqr
20	x	x	x	x			x	x	0.548	C3, d^2	d^3, da1sqr
6	x	x				x		x	0.546	C2	da1ln
7	x	x	x			x		x	0.546	C3	da1ln, d^2

Table B.6: Summary of 'best' models using transformed distance variables for the three calibration sites individually

Model	Foxwood West n= 153			Foxwood East n=172			Livingstone Street n=179		
	R^2	not in equation	t-test fail	R^2	not in equation	t-test fail	R^2	not in equation	t-test fail
2	0.611	C		0.539	C2		0.550		db1
3	0.626	C		0.539	C3	d^2	0.550		db1
6	0.631	C	dcln	0.546	C2	da1ln	0.568		Ch2 da1ln db2lnd db1ln
7	0.634	C		0.546	C3	da1ln d^2	0.569		da1ln db1ln
16	0.638	C		0.548	C2	da1sqr	0.577		Ch2 da1sqr db1sqr db2sqr
17	0.638	C	d^2	0.548	C3	da1sqr d^2	0.577		Ch2 d^2 da1sqr db1sqr db2sqr

B.4 Combinations of Variables Tested for the Speed Profile Model

Table B.7: Tested combinations of variables

	V1	*d*	*dt*	*dt²*	*dt³*	*df*	*df²*	*df³*	*H*	*T*	*C*	*Ch*
1	x		x	x		x	x		x	x	x	x
2	x	x	x	x		x	x		x	x	x	x
3	x		x	x	x	x	x	x	x	x	x	x
4	x	x	x	x	x	x	x	x	x	x	x	x
5	x			x			x		x	x	x	x
6	x	x		x			x		x	x	x	x
7	x				x			x	x	x	x	x
8	x	x			x			x	x	x	x	x
9	x			x	x		x	x	x	x	x	x
10	x	x		x	x		x	x	x	x	x	x
11	x		x		x	x		x	x	x	x	x
12	x	x	x		x	x		x	x	x	x	x
13	x		x	x	x				x	x	x	x
14	x	x	x	x	x				x	x	x	x
15	x		x	x		x	x	x	x	x	x	x
16	x	x	x	x		x	x	x	x	x	x	x

APPENDIX C

EXCEL SPREADSHEET

This section shows an Excel spreadsheet used to calculate speeds for a hypothetical traffic calming scheme using the speed profile model equation. The use of such a spreadsheet facilitates the calculation of speeds at any desired point while enabling any alteration to the database matrix to be simultaneously amended in the formulae and also in the graph embedded in the spreadsheet.

Tables C.1 and C.2 present the database matrix (columns A to K), the coefficients from the regression equation (columns O to AB) and the speeds obtained from the application of the speed profile model (column N). Tables C.3 and C.4 show the formulae written in the spreadsheet.

Table C.1: Excel spreadsheet - database matrix (columns A to N)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2	dist	disto	disfrom	disto2	disfrom2	disto3	disfrom3	hump	table	cushion	chicane		dist	**SPM**
3	0	40	50	1600	2500	64000	125000	0	0	0	0		0	34.41
4	20	30	60	900	3600	27000	216000	0	0	0	0		20	33.43
5	50	0	90	0	8100	0	729000	1	0	0	0		50	28.59
6	65	65	15	4225	225	274625	3375	0	0	0	0		65	30.52
7	80	50	30	2500	900	125000	27000	0	0	0	0		80	33.60
8	100	30	50	900	2500	27000	125000	0	0	0	0		100	32.95
9	130	0	80	0	6400	0	512000	0	0	1	0		130	29.21
10	150	53	20	2809	400	148877	8000	0	0	0	0		150	31.35
11	160	43	30	1849	900	79507	27000	0	0	0	0		160	32.77
12	180	23	50	529	2500	12167	125000	0	0	0	0		180	31.79
13	203	0	73	0	5329	0	389017	0	0	1	0		203	27.95
14	223	55	20	3025	400	166375	8000	0	0	0	0		223	31.55
15	243	35	40	1225	1600	42875	64000	0	0	0	0		243	33.04
16	263	15	60	225	3600	3375	216000	0	0	0	0		263	30.79
17	278	0	75	0	5625	0	421875	0	1	0	0		278	22.40
18	293	40	15	1600	225	64000	3375	0	0	0	0		293	27.92
19	308	25	30	625	900	15625	27000	0	0	0	0		308	30.10
20	318	15	40	225	1600	3375	64000	0	0	0	0		318	29.64
21	333	0	55	0	3025	0	166375	0	0	1	0		333	26.50
22														
23														
24														

Table C.2: Excel spreadsheet - Speed profile model coefficients (columns O to AB)

	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	V1	const	v1	d	disto	disfrom	disto2	disfrom2	disto3	disfrom3	hump	table	cushion	chicane
2	33	-8.73	0.62	0	2.30E-01	0.78	-0.0012	-0.0137	0	8.52E-05	-4.483	-6.71	-0.86	-2.01
3														
4														
5														
6														
7														
8														
9														
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11														
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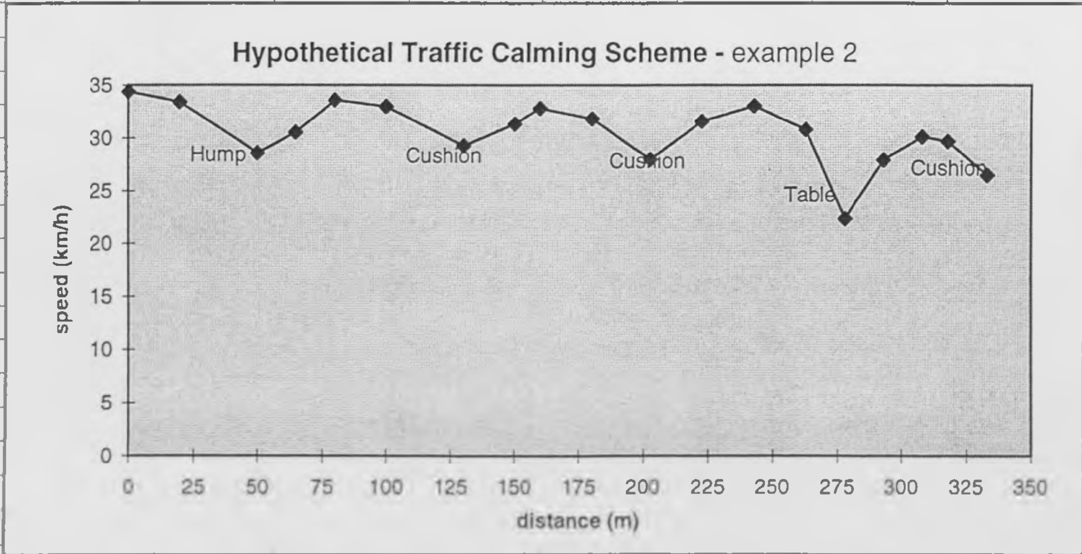

Table C.3: Excel spreadsheet - database matrix and formulae (columns A to G)

	A	B	C	D	E	F	G
1							
2	dist	disto	disfrom	disto2	disfrom2	disto3	disfrom3
3	0	40	50	=B3^2	=C3^2	=B3^3	=C3^3
4	20	30	60	=B4^2	=C4^2	=B4^3	=C4^3
5	50	0	90	=B5^2	=C5^2	=B5^3	=C5^3
6	65	65	15	=B6^2	=C6^2	=B6^3	=C6^3
7	80	50	30	=B7^2	=C7^2	=B7^3	=C7^3
8	100	30	50	=B8^2	=C8^2	=B8^3	=C8^3
9	130	0	80	=B9^2	=C9^2	=B9^3	=C9^3
10	150	53	20	=B10^2	=C10^2	=B10^3	=C10^3
11	160	43	30	=B11^2	=C11^2	=B11^3	=C11^3
12	180	23	50	=B12^2	=C12^2	=B12^3	=C12^3
13	203	0	73	=B13^2	=C13^2	=B13^3	=C13^3
14	223	55	20	=B14^2	=C14^2	=B14^3	=C14^3
15	243	35	40	=B15^2	=C15^2	=B15^3	=C15^3
16	263	15	60	=B16^2	=C16^2	=B16^3	=C16^3
17	278	0	75	=B17^2	=C17^2	=B17^3	=C17^3
18	293	40	15	=B18^2	=C18^2	=B18^3	=C18^3
19	308	25	30	=B19^2	=C19^2	=B19^3	=C19^3
20	318	15	40	=B20^2	=C20^2	=B20^3	=C20^3
21	333	0	55	=B21^2	=C21^2	=B21^3	=C21^3
22							
23							
24							

Table C.4: Excel spreadsheet - Speed profile model formulae (column N)

	N
1	
2	**SPM**
3	=$P$2+($Q$2*$O$2)+(A3*$R$2)+($S$2*B3)+(C3*$T$2)+($U$2*D3)+(E3*$V$2)+(F3*$W$2)+(G3*$X$2)+($Y$2*H3)+($Z$2*I3)+(J3*$AA$2)
4	=$P$2+($Q$2*$O$2)+(A4*$R$2)+($S$2*B4)+(C4*$T$2)+($U$2*D4)+(E4*$V$2)+(F4*$W$2)+(G4*$X$2)+($Y$2*H4)+($Z$2*I4)+(J4*$AA$2)
5	=$P$2+($Q$2*$O$2)+(A5*$R$2)+($S$2*B5)+(C5*$T$2)+($U$2*D5)+(E5*$V$2)+(F5*$W$2)+(G5*$X$2)+($Y$2*H5)+($Z$2*I5)+(J5*$AA$2)
6	=$P$2+($Q$2*$O$2)+(A6*$R$2)+($S$2*B6)+(C6*$T$2)+($U$2*D6)+(E6*$V$2)+(F6*$W$2)+(G6*$X$2)+($Y$2*H6)+($Z$2*I6)+(J6*$AA$2)
7	=$P$2+($Q$2*$O$2)+(A7*$R$2)+($S$2*B7)+(C7*$T$2)+($U$2*D7)+(E7*$V$2)+(F7*$W$2)+(G7*$X$2)+($Y$2*H7)+($Z$2*I7)+(J7*$AA$2)
8	=$P$2+($Q$2*$O$2)+(A8*$R$2)+($S$2*B8)+(C8*$T$2)+($U$2*D8)+(E8*$V$2)+(F8*$W$2)+(G8*$X$2)+($Y$2*H8)+($Z$2*I8)+(J8*$AA$2)
9	=$P$2+($Q$2*$O$2)+(A9*$R$2)+($S$2*B9)+(C9*$T$2)+($U$2*D9)+(E9*$V$2)+(F9*$W$2)+(G9*$X$2)+($Y$2*H9)+($Z$2*I9)+(J9*$AA$2)
10	=$P$2+($Q$2*$O$2)+(A10*$R$2)+($S$2*B10)+(C10*$T$2)+($U$2*D10)+(E10*$V$2)+(F10*$W$2)+(G10*$X$2)+($Y$2*H10)+($Z$2*I10)+(J10*$AA$2)
11	=$P$2+($Q$2*$O$2)+(A11*$R$2)+($S$2*B11)+(C11*$T$2)+($U$2*D11)+(E11*$V$2)+(F11*$W$2)+(G11*$X$2)+($Y$2*H11)+($Z$2*I11)+(J11*$AA$2)
12	=$P$2+($Q$2*$O$2)+(A12*$R$2)+($S$2*B12)+(C12*$T$2)+($U$2*D12)+(E12*$V$2)+(F12*$W$2)+(G12*$X$2)+($Y$2*H12)+($Z$2*I12)+(J12*$AA$2)
13	=$P$2+($Q$2*$O$2)+(A13*$R$2)+($S$2*B13)+(C13*$T$2)+($U$2*D13)+(E13*$V$2)+(F13*$W$2)+(G13*$X$2)+($Y$2*H13)+($Z$2*I13)+(J13*$AA$2)
14	=$P$2+($Q$2*$O$2)+(A14*$R$2)+($S$2*B14)+(C14*$T$2)+($U$2*D14)+(E14*$V$2)+(F14*$W$2)+(G14*$X$2)+($Y$2*H14)+($Z$2*I14)+(J14*$AA$2)
15	=$P$2+($Q$2*$O$2)+(A15*$R$2)+($S$2*B15)+(C15*$T$2)+($U$2*D15)+(E15*$V$2)+(F15*$W$2)+(G15*$X$2)+($Y$2*H15)+($Z$2*I15)+(J15*$AA$2)
16	=$P$2+($Q$2*$O$2)+(A16*$R$2)+($S$2*B16)+(C16*$T$2)+($U$2*D16)+(E16*$V$2)+(F16*$W$2)+(G16*$X$2)+($Y$2*H16)+($Z$2*I16)+(J16*$AA$2)
17	=$P$2+($Q$2*$O$2)+(A17*$R$2)+($S$2*B17)+(C17*$T$2)+($U$2*D17)+(E17*$V$2)+(F17*$W$2)+(G17*$X$2)+($Y$2*H17)+($Z$2*I17)+(J17*$AA$2)
18	=$P$2+($Q$2*$O$2)+(A18*$R$2)+($S$2*B18)+(C18*$T$2)+($U$2*D18)+(E18*$V$2)+(F18*$W$2)+(G18*$X$2)+($Y$2*H18)+($Z$2*I18)+(J18*$AA$2)
19	=$P$2+($Q$2*$O$2)+(A19*$R$2)+($S$2*B19)+(C19*$T$2)+($U$2*D19)+(E19*$V$2)+(F19*$W$2)+(G19*$X$2)+($Y$2*H19)+($Z$2*I19)+(J19*$AA$2)
20	=$P$2+($Q$2*$O$2)+(A20*$R$2)+($S$2*B20)+(C20*$T$2)+($U$2*D20)+(E20*$V$2)+(F20*$W$2)+(G20*$X$2)+($Y$2*H20)+($Z$2*I20)+(J20*$AA$2)
21	=$P$2+($Q$2*$O$2)+(A21*$R$2)+($S$2*B21)+(C21*$T$2)+($U$2*D21)+(E21*$V$2)+(F21*$W$2)+(G21*$X$2)+($Y$2*H21)+($Z$2*I21)+(J21*$AA$2)
22	

APPENDIX D

CORRELATION MATRIX - Speed Profile Model

This appendix complements the analysis of the model specification by introducing the correlation matrix in order to examine the partial correlations among the variables included in the speed profile model.

Table D.1: Correlation matrix - weighted least squares regression

	Ch	*T*	*H*	*C*	*V1*	dt^2	df^3	*df*	*dt*	df^2
Ch		0.22	0.26	0.48	0.01	-0.36	-0.42	-0.30	0.39	0.37
T			0.24	0.37	-0.08	-0.38	-0.01	-0.04	0.41	0.03
H				0.37	-0.09	-0.35	-0.03	-0.04	0.37	0.04
C					-0.04	-0.58	-0.22	-0.20	0.63	0.22
V1						0.03	0.01	0.02	0.01	-0.01
dt^2							0.36	0.47	-0.94	-0.43
df^3								0.92	-0.35	-0.98
df									-0.39	-0.97
dt										0.40
df^2										

The examination of partial correlations indicates no collinearity problem as attested by the above correlation matrix (Table D.1). It should be noted that *dt* and *df* are highly correlated to their respective powers. Nevertheless, terms like df^2, df^3, are all nonlinear functions of *df,* and hence strictly speaking do not violate the no multicollinearity assumption.