KTH School of Architecture and the Built Environment

Speed characteristics of urban streets based on driver behaviour studies and simulation

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Abstract

The objective of the study was to gain in-depth knowledge of speed relationships for urban streets. The speed characteristics were examined using a number of methods for data collection. Throughout the research, a special focus was placed on capturing the influence on driver speed of interactions with pedestrians, cyclists and other road users, called side-friction events in this study.

First, driver behaviour and travel time data was collected from field and driving simulator studies for a range of street types and traffic conditions. The collected data was used to calibrate a microscopic traffic simulation model. Production runs with this model were performed for various traffic conditions. Second, aggregated speed data was collected at the link level, i.e. the macro level, for three street types. In combination with street site variables, speed and flow data was analysed using multiple regression techniques with space mean speed as dependent variable. This analysis was also performed for average travel speed data produced by microscopic traffic simulation.

Two central results were attained and utilized for the model development:

- In-depth knowledge of which factors influence speed choice on urban street links with minor intersections, on a micro and macro level.
- A comprehensive research methodology for study of speed characteristics on urban streets in which the knowledge gained at the micro and macro level was applied.

Results from the micro study showed that *Average number of crossing pedestrians* and *Traffic flow* had significant impact on average travel speed (R^2=0.91). Results from the macro study performed for three street types showed that *Street function* and *Number of lanes* also had a high degree of explanation (R^2 close to 0.70). The variables *Separated bicycle lane, Roadside parking permitted* and *Number of minor intersections per 1 km* were significant for some of the street types modelled in the macro study. The variables *Ratio of through vehicles* and *Gender of the driver* were also investigated and were found not to influence space-mean speed. The macro study demonstrated that speed choice and driver behaviour were consistent for each street type investigated regardless of city type and population size. The speed-flow relationships of the micro model for an urban street type showed good agreement with the macro model for traffic flows in the upper range. In conclusion, the research effort showed that the included side-friction variables added explanatory value to the estimation of speed, and thus can enhance the knowledge of traffic impacts of different urban street designs.

Keywords: Speed, Characteristics, Urban area, Road network, Street, Traffic, Driver, Side-friction element, Driving simulator, Simulation, Behaviour, Measurement, Micro, Macro, Mathematical model

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Stockholm, December 2006

Karin Aronsson

[1] The project group working on specific parts of the Swedish Road Administration's Impact Assessment Catalogue. EMV is an abbreviation of Effekt Modeller för Vägtrafikanläggningar.

Contents

Summary

Background and objective

Knowledge of how the street network and streets should be designed to promote road safety has grown in Sweden over a long period, and has also been implemented in the Swedish Impact Assessment Catalogue. However, relationships between speed, street design and interaction with pedestrians and cyclists, buses stopping at stops, vehicles parking in or leaving on-street parking places, have not been included. Therefore, the aim of the study was to gain in-depth knowledge of these relationships including interactions with other road users in Swedish urban conditions.

Methodology

The research effort was pursued in a bottom- up perspective and comprised driver behaviour studies and traffic simulation modelling. The influence of street factors and interaction with other road users, called side-friction factors, were given primary focus. Two methods for the investigation of speed on urban street links with minor intersections were developed, comprising new techniques for data collection and systematisation of the evaluation process. The first method – the micro study – modelled average travel speed results produced by a microscopic traffic simulation model calibrated by using observed driver behaviour. The input data were collected by mobile studies, area-wide video tower recordings, travel time studies, spot speed measurements and pedestrian and bicycle flow counts. In the second method – the macro study – space-mean speed data was modelled for three street link types based on aggregated speed data collected in the field. The macro models developed for three street types were compared with speed-flow relationships presented in the Swedish Impact Assessment Catalogue, and with the micro model performed for one street type.

Results and discussion

Several significant variables influencing speed were identified in the analysis using collected field data and driving simulator results: *Traffic flow; Pedestrian and bicycle movements*; *Buses entering and exiting from bus stops*; *Vehicles waiting on side streets* and *Street type and design*. These results were used as a basis for simulation model calibration. The microscopic traffic simulation model produced travel time estimates for undisturbed trips within four percent of field travel time data. Multiple regression analysis of simulations results showed that *Number of crossing pedestrians* had a significant impact on average travel speed. *Traffic flow* was also significant. The resulting equation from the micro study was

$$\bar{v}_{sim} = 48.7 - 0.011 \times Flow - 0.015 \times Ped$$

where

$\bar{v}_{sim}$ = average travel speed (km/h) from simulation runs
$Flow$ = traffic flow per hour in both directions of travel
Ped = number of crossing pedestrians per hour and kilometre

The results of the regression analysis of speed data in the macro study showed *Average number of crossing pedestrians and cyclists*, *Traffic flow*, *Street function* and *Number of*

lanes to have a high degree of explanation. The variables *Separated bicycle lane*, *Road-side parking permitted* and *Number of minor intersections per 1 km* were significant for some of the street types. The R2 values of the models were close to 0.70. The variables *Percentage of through vehicles* and *Gender of the driver* were also investigated and were found not to influence space mean speed. The study was performed for three street types with a posted speed limit of 50 km/h, and for all streets types combined. The resulting macro models were:

Arterials $\bar{v}_{obs} = 63.8 - 0.087 \times Flow - 8.61 \times Func - 2.44 \times Inter$

Suburban streets $\bar{v}_{obs} = 55.9 - 0.072 \times Flow - 0.414 \times Ped - 5.30 \times Func + 5.80 \times Lanes - 3.83 \times Bus$

Urban streets $\bar{v}_{obs} = 39.8 - 0.202 \times Flow - 0.237 \times Ped + 5.24 \times Lanes + 4.73 \times BicSep - 5.54 \times Park$

All street types $\bar{v}_{obs} = 60.2 - 0.121 \times Flow - 0.619 \times Ped - 5.42 \times Func + 3.11 \times Lanes - 6.13 \times Park - 0.60 \times Inter$

where

$\bar{v}_{obs}$	=	Observed space mean speed (km/h)
Flow	=	Observed average traffic flow in the studied direction of travel expressed in vehicles per 5 min
Ped	=	Average number of crossing pedestrians and cyclists (summarized in groups of 5, 15 and 25 people per 15 min and 400 m)
Func	=	Street function (thoroughfare or approach = 0; other link in main network = 1)
Lanes	=	Number of lanes in the studied direction (1 or 2).
BicSep	=	Separated bicycle lane (yes=1; no = 0)
Park	=	Roadside parking permitted (yes=1; no=0)
Bus	=	Roadside bus stop exists on link (yes=1; no=0)
Inter	=	Number of minor intersections per 1 km

Results of the micro study for an urban street type were compared with the analysis performed in the macro study. The speed-flow relationships in the macro model showed good agreement with the micro model for traffic flows in the upper range.

The conclusion from the field study of male and female drivers was that they differed only marginally in their speed and headway driving behaviour. The simulator study showed no difference in behaviour between men and women for the event *arriving at a crosswalk with approaching pedestrians*. The female subjects reduced their speed more than male subjects did for the event *passing of an occupied bus stop*.

The macro study showed that speed choice and driver behaviour were consistent for each street type investigated regardless of city type and population size.

The macro models were compared with speed-flow relationships of the equivalent street type in the Swedish Impact Assessment Catalogue. The macro model for arterial links and the model for suburban street links, for the street function Thoroughfare or approach, generally agree with the speed-flow relationships of equivalent street types presented in the Impact Assessment Catalogue. The macro model for urban street links, which included several significant side-friction variables, gave lower speed results than models in the Impact Assessment Catalogue. The results of the macro model for urban street links were supported by average travel speed field data. In conclusion, the included side-friction variables added explanatory value to the estimation of speed characteristics.

Recommendations for further research

In this study an extensive amount of data was collected, analyzed and applied for modelling of speed relationships as a basis for the presented conclusions. Although adequate for the scope and objectives of the study, the methods could be developed further to gain enhanced knowledge of driver behaviour in an urban traffic environment. In particular, the following suggestions are made:

- Data collection methods may be improved and carried out more efficiently.

- The experimental design including the use of a driving simulator could be made more advanced.

- The microscopic traffic simulation model can be further developed.

- Further development of the strategy including methods for synthesis of the results of the “bottom-up” and “top-down” techniques.

- The enhanced “toolbox” for analysis of factors that affect speed choice and speed patterns could be applied for study of other combinations of parameters and contexts.

1. INTRODUCTION

This chapter covers the background, objective, scope, research strategy, and structure of the study.

1.1 BACKGROUND

The main goal of the Swedish Transportation policy is to provide a socio-economically efficient transportation system that is sustainable in a long-term perspective for people and goods. This goal was set by the Swedish Government in 1998 (prop. 1997/98:56) with the objectives of increasing mobility and traffic safety and providing a good environment, high transport quality, a positive regional development and equal opportunities for male and female users. The focus on a safer traffic environment was affirmed by the Swedish Government when Parliament adopted the Road Traffic Safety Bill founded on the ”Vision Zero” philosophy (prop. 1996/97:137). The bill declared that the long-term objective is that no one will be killed or seriously injured in the Swedish road transport system, and that the design and operation of the road transport system must be brought into line with the requirements for meeting this goal. 440 people were killed and approximately 4,000 were seriously injured on Sweden’s roads in 2005, corresponding to 50 individuals killed in traffic per million inhabitants. An interim target of Vision Zero is that traffic fatalities should be reduced by a minimum of fifty percent within ten years. The final target is to achieve Vision Zero by 2017 or sooner.

Knowledge of how the street network and streets should be designed to promote road safety has grown in Sweden over a long period has been documented in the handbooks SCAFT1968 (Nordqvist and Gunnarsson 1968), The Catalogue of Measures (Linderholm 1996a), Calm Streets! (Brandberg, Johansson, and Gustafsson 1999), Planning Guidelines abbreviated TRAST (Johansson, Nilsson, Wallberg et al. 2004), Road and Street Design Handbook abbreviated VGU (Swedish Road Administration 2004), and the Swedish Road Administration’s Impact Assessment Catalogue (Swedish Road Administration 2001a) to give a few examples. This literature contains examples of how streets can be designed and equipped with calming measures to reduce motor vehicle speed. The examples primarily describe measures to ensure that a posted speed limit of 30 km/h is adhered to. Regardless of the speed-reducing measure applied, driving behaviour varies widely, and the Road Design Manual VU94 (Swedish Road Administration 1999), contains the following observation with regard to reference speed for street alignment: ”Many road users exceed the posted speed limits. This is both a road safety and an environmental issue. Knowledge and experience of how road environments can be designed so that road users choose to drive in accordance with the posted speed limits is limited.” Drivers’ speed choice relates to factors such as individual driver behaviour, design and regulation of the street, traffic flow at the time, and the influence of other motorists. The consequences of driving at high speed on streets in urban areas are reduced traffic safety for all road users, reduced accessibility for non-motorized road users, influence on the total traffic performance of the street and environmental impacts such as more noise and increased exhaust emissions.

A national survey found that half of the vehicle kilometres driven on roads in built-up areas exceeded the posted speed limit (Nilsson 2001). The posted speed limit of 50 km/h on roads in urban areas was exceeded on average by 3 km/h for all driven vehicle kilometres. The speed limit was exceeded by on average 7 km/h for the vehicle kilometres driven by speeders. The length of streets in urban areas of Sweden measures 40 thousand kilometres[2]; the rural road network comprises over two hundred thousand kilometres. Vehicle kilometres run on municipally controlled streets and on state roads with a posted speed of 50 km/h accumulated to 25 billion vehicle kilometres. Half of the serious personal injuries and one fourth of fatal accidents caused by road traffic occur on streets or roads with a posted speed of 50 km/h (Englund, Gregersen, Hyden et al. 1998). It is therefore of great importance to improve knowledge of what influences drivers' speed choices on urban roads.

Models for operating speed have been developed for rural roads, but are less well developed in an Swedish urban context. A review of geometric design research in the U.S. (Fitzpatrick and Wooldridge 2001) identifies a demand for a revised design manual, which should include design consistency concepts, and strengthened guidelines for consideration of pedestrian and bicycle movement. In Sweden, guidelines (see above) on the implementation of physical measures in urban mixed traffic streets have been published by the Road Administration and the Association for Local Authorities. However, methods for cost efficiency and safety analysis of an investment in urban streets have not yet been outlined. Thus, there is a need for increased knowledge of what influences vehicle speed on urban streets, to be used as input in the design guidelines for urban streets to operate at the assigned speed.

1.2 OBJECTIVES

Motor vehicle speeds on urban streets are influenced by a great many factors, including geometric design, the surrounding land use, traffic flow and degree of conflict with pedestrians, cyclists, buses, kerbside parking, exits from roadside premises and individual driving behaviour. The objective of the thesis was to gain in-depth knowledge of these relationships for a variety of street types and urban settings. In a later stage the results can be used as input in the design guidelines for urban streets to study the impact of speed on safety and traffic performance for all road users. They also make it possible to evaluate the outcome of alternative street design, roadside features, traffic engineering considerations etc on drivers' speed and, if needed, re-design the proposed facility in order to achieve the assigned speed.

An objective of a sub-study, performed within the presented study, was to establish if there are significant differences in driving behaviour between male and female drivers for a variety of urban street designs, environments and traffic conditions.

1.3 SCOPE

The research deals with data collection, analysis and modelling of individual driver speed adaptation resulting from actual events such as interaction with other road users, when driving on the major urban street network. The studied urban street segment types are arterials, suburban streets and urban streets. A detailed description of the types is given in Chapter 3. The studied urban street segments include minor intersections where traffic on the studied streets have right of way. A minor intersection is defined as an intersection with fewer than one thousand incoming motor vehicles per day on each sec-

[2] The Swedish Road Administration Annual Report, 2005.

ondary approach to the intersection. The recently developed Swedish Planning Guidelines (TRAST) and the Road and Street Design Handbook (VGU) present the concept of street environment description. The two planning handbooks indicate the necessity to acknowledge the street environment and to incorporate it in the design process. The TRAST handbook defines the street environment in terms of

- Character (structure, aesthetics, street environment, architectural style etc)
- Traffic network (pedestrians, bicycles, vehicles; main or local network etc)
- Speed (walking speed, 30 km/h, 50/30, 50, 70/50, 70, 90 and 110 km/h)
- Special qualities (kerbside parking, light poles, separation of traffic etc)

These factors constitute a platform for the urban planning process, and are a bridge to the street design directions presented in the Road and Street Design Handbook. The handbooks manifest the importance of distinguishing various street environments, which is in line with the scope of the present study.

The influence of through traffic ratio on driver behaviour was investigated in the study, as were differences in driver behaviour between male and female drivers. Distractions within the vehicle influencing the driving performance have been covered in international studies (Stutts, Feaganes, Rodgman et al. 2003) and are not investigated in this thesis.

1.4 RESEARCH STRATEGY

The research strategy consisted of two modes of investigation:

- micro study of individual driver speed behaviour, and
- macro study of traffic characteristics, at the link level.

The micro study entailed a bottom-up approach to the research problem. The empirical data, collected at the individual driver behaviour level, enabled microscopic simulation, calibration and modelling. Microscopic modelling was utilized with the purpose of producing speed-flow relationships for a variety of traffic conditions. The macro study investigated traffic characteristics at the link level. Speed and flow data, combined with street site variables, were analysed by multiple regression technique with space mean speed as the dependent variable. Finally a synthesis of speed models was performed based on the micro and macro studies.

1.5 STRUCTURE OF THE THESIS

The thesis is structured in six chapters. The first two chapters describe the background, problem statement, objective and scope, concluding with a literature review. Chapter three presents the chosen research methodology and the results of the empirical micro and macro studies are detailed in chapter four. The implementation of the empirical results in a traffic model is described in chapter five and chapter six contains a synthesis, conclusions and considerations for further research.

2. LITERATURE REVIEW

The central issue in the literature review was to clarify the relationships between *traffic performance* and *street design*. Performance is part of the characteristic known as accessibility and describes road users' time consumption in their movements in the traffic network (Brandberg et al. 1999). The time consumed is dependent upon the length and speed of the movement, where the length is determined by the design of the traffic network and speed is, for example, dependent upon link design and traffic flow. In other words, *speed* is the most appropriate measure of performance on urban streets, and is therefore used throughout the report.

Knowledge regarding speed impacts relevant to the purpose of this thesis gained from the studied literature has been documented in seven sections of chapter 2. The first two sections give an overview of the terms used and the general theory of traffic flow for road links. A review of speed performance measures, data collection and analysis methods is documented in section three. The fourth section deals with the effect of the design and control conditions. The fifth section details the available knowledge about the influence of interaction with pedestrians, cyclists, and public transport. Literature referring to female and male driver behaviour is reviewed in section six, which also includes a general review of qualitative and quantitative driver behaviour with regards to gender. Lastly, in section seven, some conclusions based on the literature reviews are given.

2.1 GLOSSARY OF TERMS

The following definitions are used in the thesis:

Traffic characteristics

Average travel speed ($\bar{v}$)	The average speed of a traffic stream travelling on a segment or route, computed as the length divided by the average travel time of the vehicles traversing it.
Density (d)	The number of vehicles (or pedestrians) occupying a given length of a lane or roadway at a particular instant.
Free-flow speed (v_f)	Speed when no constraints are placed on a driver by other vehicles on the road ahead, driving in the same direction.
Space mean speed ($\bar{v}_s$)	The harmonic mean of speed over a length of roadway $N\left(\Sigma(v_i)^{-1}\right)^{-1} = N\Delta L(\Sigma\Delta t_i)^{-1}$; or the average speed based on the average travel time of vehicles to traverse a segment of roadway; in kilometres per hour.
Speed (v)	A rate of motion expressed as distance per unit of time.
Speed profile	A diagram of distance and speed data of vehicle movement on a road or street.
Spot speed (v_i)	The vehicle speed collected at a short-base station when traversing it. Also called point speed.
Time mean speed ($\bar{v}_t$)	The arithmetic mean of speed over a length of roadway $\frac{1}{N}\Sigma v_i = \frac{\Delta L}{N} * \Sigma(\Delta t_i)^{-1}$
Traffic flow (q)	The total number of vehicles that pass over a given point or section of a lane or roadway during a given time interval.

General

Arterial	A street which serves through traffic and to some extent local traffic. Pedestrian and bicycle facilities are separated from the roadway.
Carriageway	The travelled way excluding shoulders.
Driving simulator	A reproduction of motor vehicle driving in a computer environment. The subject drives a vehicle in a synthetic street and inter-

	acts with the road users on it.
Empirical model	A model that describes system performance based on the statistical analysis of observational data.
HCM2000	Highway Capacity Manual 2000 (Transportation Research Board 2000)
Long-base route	A predefined route between two short-base stations.
Macroscopic model	A mathematical model in which the traffic movement is conceptualized as a fluid on the link level.
Microscopic model	A mathematical model that captures the movement of individual vehicles including interactions with other road users.
Roadway	The whole of the travelled way, median and outer separators.
Short-base station	A measurement point where traffic flow, vehicle type, direction, passage time and space mean peed data is collected.
Side-friction	Impact on traffic performance of driver interaction with pedestrians, cyclists, buses at bus stops, kerbside parking, or vehicles entering and exiting the studied street.
Simulation model	A computer model that uses mathematical models to conduct experiments with traffic events on a transportation facility or system over extended periods of time.
SRA	Swedish Road Administration
Suburban street	A street with low-density driveway access on the periphery of an urban area. The street type has mixed motorised and un-motorised traffic.
Through traffic	Vehicles passing through the studied long-base area constituted through traffic.
Travelled way	The portion of the road designed exclusively for motor vehicles; running, stopped or parked (including shoulders).
Urban street	A street located in a the city centre. Comprises mixed motorised and un-motorised traffic.

2.2 GENERAL THEORY OF TRAFFIC FLOW FOR ROAD LINKS

Traffic movement on a roadway can be described by three fundamental variables called traffic flow, speed and density (Transportation Research Board 2000). The traffic stream can be uninterrupted or interrupted, which is mainly dependent on the road facility type. Uninterrupted-flow road facilities have little degree of interruption, for example from traffic control or interaction with entering and exiting traffic. Interrupted-flow road facilities have a large degree of traffic control and fixed interruption points which, regardless of traffic amount, impact upon the traffic performance.

The traffic flow can be collected for one direction or both according to the context. It can be expressed in terms of annual, daily, hourly, or sub-hourly periods.

The average travel speed ($\overline{v}$) is calculated from data of n vehicles traversing a segment of length L with the travel times $t_1, t_2, t_3, \ldots, t_n$ as stated in equation 2.1.

$$\overline{v} = \frac{n \times L}{\sum_{i=1}^{n} t_i} = \frac{L}{\frac{1}{n}\sum_{i=1}^{n} t_i} = \frac{L}{\overline{t_a}} \qquad (2.1)$$

Where

$\overline{v}$	=	average travel speed (km/h)
L	=	length of the road segment (km)
t_i	=	travel time of the ith vehicle to traverse the segment (h)
n	=	number of travel times observed
$\overline{t_a}$	=	average travel time over L (h)

The travel times in this calculation include stopped time and delay due to intersections or traffic congestion.

The average travel speed is equivalent to space mean speed, which is defined as

(1) the harmonic mean of speed over a length of roadway;

(2) an average speed based on the average travel time of vehicles to traverse a segment of roadway.

The space mean speed (1) is calculated using equation 2.2, which leads to the second definition (2) of space mean speed defined in equation 2.1.

$$\text{Space mean speed} = \frac{n}{\sum_{i=1}^{n} \frac{1}{v_i}} = \frac{n \times L}{\sum_{i=1}^{n} t_i} = \frac{L}{\frac{1}{n}\sum_{i=1}^{n} t_i} = \frac{L}{\overline{t_a}} = \overline{v}_s \qquad (2.2)$$

Density (k) is the number of vehicles occupying a given length of a roadway at a particular instant, and is calculated using equation 2.3.

$$k = \frac{n}{L} \qquad (2.3)$$

Where

k	=	density (veh/km)
L	=	length of the road segment (km)
n	=	number of vehicles occupying an observed length

Direct measurement of density requires elevated photographing of the roadway, and in its Highway Capacity Manual 2000 (HCM2000), the Transportation Research Board recommends that the measure be computed from the average travel speed and flow rate, see equation 2.4, for the conditions that speed and density are constant – which for example prevails for undersaturated traffic conditions. The term flow rate (q_r) is defined as the equivalent hourly rate at which vehicles pass over a given point during a time interval of less than one hour.

$$k = \frac{q_r}{\overline{v}_s} \qquad (2.4)$$

Where

k	=	density (veh/km)
q_r	=	flow rate (veh/h)
$\overline{v}_s$	=	space mean speed (km/h)

The parameter density is also connected to the parameters of spacing and headway. Spacing is the distance from the front of a vehicle to the front of the one directly ahead. Headway is defined as the time between successive vehicles as they pass a point on a lane or a roadway, and usually collected in the units of seconds. Moreover, the HCM 2000 states "these characteristics are microscopic, since they relate to individual pairs of vehicles within the traffic stream. Within any traffic stream, both the spacing and the headway of individual vehicles are distributed over a range of values, generally related to the speed of the traffic stream and prevailing conditions. In the aggregate, these microscopic parameters relate to the macroscopic flow parameters of density and flow rate."

The average vehicle spacing in a traffic stream can be used to compute the density of the traffic stream, as stated in equation 2.5.

$$Density = \frac{1}{spacing} \qquad (2.5)$$

The average headway of a traffic steam is equal to the average spacing divided by speed.

The basic relationship of density, flow rate and space mean speed given in equation 2.4 describe an uninterrupted traffic stream. Placing traffic flow first, the formula is according to equation 2.6. The relationship presented in the equation is developed for an uninterrupted traffic stream.

$$q = k * \bar{v}_s \tag{2.6}$$

Where

q	=	traffic flow (veh/h)
k	=	density (veh/km)
$\bar{v}_s$	=	space mean speed (km/h)

The parameters q, k and $\bar{v}_s$ in the formula are stochastic and dependent. The relationships can be generalized and exemplified for various traffic conditions, see Figure 2:1.

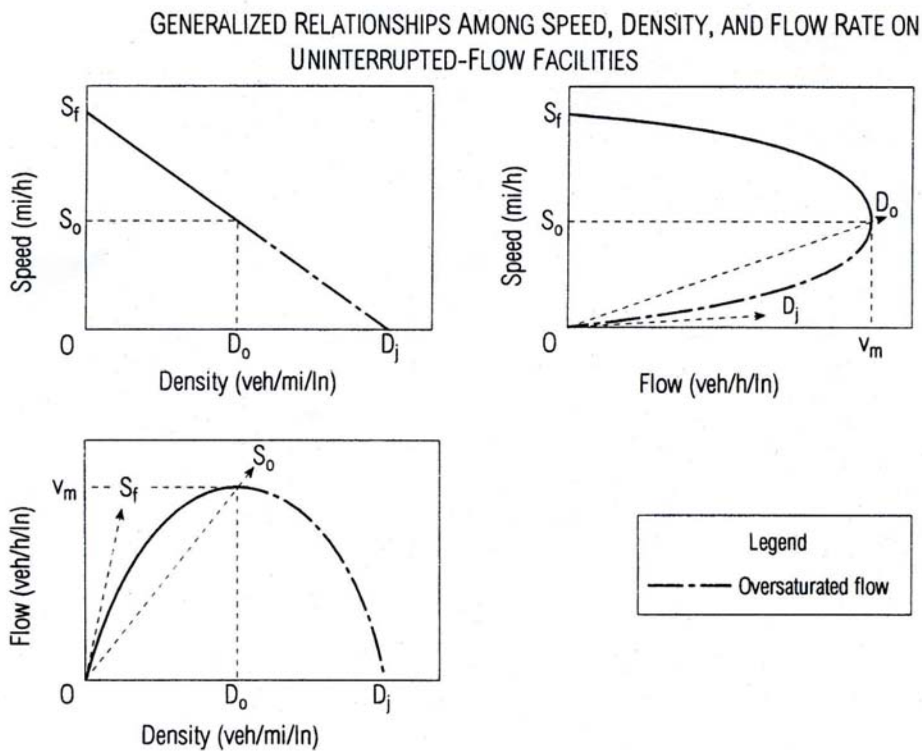


Figure 2:1 Generalized relationships between speed, density, and flow rate on uninterrupted-flow facilities. Source (Transportation Research Board 2000).

The first diagram in Figure 2:1 illustrates a traffic situation where driver speed (S) is initially high and density (D) low. Increased density will lead to a reduction in speed and through flow of vehicles, which is also shown in the second and third diagram in the figure. The maximum density (D_j), called jam density, results in very low or zero average travel speed. An optimal degree of density (D_o) leads to optimal driven speed (S_o) and the greatest amount of through flow of traffic (V_m).

2.3 DATA COLLECTION AND ANALYSIS METHODS

2.3.1 General

Research methodology

For the process of analysing relationships between various factors, the following methods are often applied.

a) *Making and testing of a hypothesis.* Statistical analysis of investigated factors can be used for testing a hypothesis, i.e. to investigate if the relationships are statistically significant or not.

Mathematical modelling of factors can be applied to explore the relationship between a dependent and one or more significant independent variables. Two different types of mathematical modelling can be identified:

b) *Empirical modelling.* This is a common type of modelling when a large amount of data is available for statistical analysis. Normally, multiple regression technique are used to develop and test the fit of a number of pre-defined mathematical functions. The functions to be tested can be obtained from literature references or found by assessing graphical plots of the data.

   Empirical modelling has the following inherent weaknesses;
   - It is restricted to the range of the existing data, i.e. it should not be used to extrapolate results outside this range.

   - Multiple regression analysis is based on the assumption that there is no correlation between the independent variables. If a strong correlation exists, the results of multiple regression analysis can often be illogical and meaningless despite very large samples.

c) *Explanatory modelling.* In this type of modelling, the researcher has an idea pf how key elements are affected by the value of certain parameters. As a typical traffic engineering example, the capacity of a minor road approach in an unsignalised intersection with a major road can be assumed to be affected by the availability of gaps in the major road traffic and the likelihood (probability function) that drivers waiting first in line in the minor road queue will accept a gap of a certain size.

   If an explanatory model can be developed, statistical analysis can be used to determine the parameter values of the model that give the best fit to the experimental data. The model can then be validated against other data describing conditions outside the range of the original study.

Data collection and analysis

Concerning traffic studies, the following general types can be distinguished.

i) *Descriptive investigations* with the purpose of explaining the present situation (e.g. traffic flow, speed, travel time, mode choice in a predefined facility or region, driver characteristics).

ii) Data collection of road user behaviour or route choice. The purpose of collecting data is for example to calibrate behavioural parameters in a model for predicting traffic volume in a network, destination distribution, mode choice and route choice. Another purpose is to be able to calibrate simulation models that aim to describe traffic volumes, speed, travel time, mode choice, emissions etc.

iii) Data collection for development and validation of models. In this type of measurement data is collected for with the intention of explaining and analyzing the relationship between various variables, e.g. traffic flow, geometric design and speed.

The present study aimed to apply all of the three types for data collection and analysis.

2.3.2 Review of applied methods for colleting speed data

In the literature, several reports recommend the use of space mean speed when reducing and analysing travel time data and traffic data (Bang, Carlsson, and Palgunadi 1995; Nilsson 2001; Turner, Eisele, Benz et al. 1998; Wardrop 1952). The measure is equivalent to harmonic mean of speed and is applicable on measurements of both spot speed and travelled speed over a distance. Space mean speed is also related to density and flow as defined in equation 2.6.

Numerous studies measure speed on rural roads and in free flow traffic conditions. The free vehicles are in many studies defined as having a minimum headway of 5 seconds to the vehicle ahead (Fitzpatrick, Elefteriadou, Harwood et al. 2000; Stenbäck 2000).

The focus of the present study is on factors influencing drivers' speed choice while travelling on urban streets, with special concentration on geometric design, urban environment and side-friction events. When reviewing the relevant literature, the most similar research found on this matter was that of Bergh, Bang et al., Ericsson, Fitzpatrick et al., Hakamies-Blomqvis and Henriksson, Lundberg, and Östlund, Jonsson, Karlgren, Nilsson, Towliat, and Wang et al.. Numerous methods of data collection are used for the purpose of these studies ranging from spot-speed measurements, travel time studies, environmental data collection as well as recording speed profiles and driving patterns. More specifically, the methods used implied traffic counts, spot-speed measuring by radar or traffic count meters, on-site observations, laser-speed measurements over a distance, car-following studies with instrumented vehicles, test subjects' driving instrumented vehicles and/or in a driving simulator.

Bang, Carlsson and Palgunadi studied speed-flow relationships for interurban roads in Indonesia by use of empirical data, regression techniques and microscopic simulation (Bang et al. 1995). The study was conducted on two-lane undivided roads and the empirical data collected comprised traffic volumes, vehicle types, spot-speed data, travel time, width of the carriageway, shoulder width, cross-section information and environmental descriptions including so-called side friction. The spot-speed was measured by double pneumatic tubes.

Ericsson (2000) investigated driving patterns in a large Swedish observational study. Thirty families in a mid-sized Swedish town participated. Each test subject borrowed a specially equipped vehicle of similar size and performance to their own car. These were equipped with a GPS receiver to register the locations driven to and driving patterns. Data on variations in driving patterns, i.e. speed and acceleration profiles, was collected to test and design a model for the relation between driving pattern factors and different street environment variables. Similar technique of data collection by use of data-logging of speed, position and time have been applied in for example the National ISA trials (Várhelyi, Hjälmdahl, Hydén et al. 2004).

In a U.S. project, prediction of speed for two-lane rural roads has been studied and calculated (Fitzpatrick et al. 2000). Speed data of free vehicles were collected using traffic counts from piezoelectric sensors and radar meters. Information on vehicle type was gathered by on-site observations and/or by traffic counts. The data was collected during off-peak periods for at least 100 observations at each site. Vehicle acceleration and deceleration speed data was also collected for the speed profile model. For this model, a variety of data was collected at each site, including alignment geometry, width of the carriageway, width of the lanes, cross-section information, weather conditions, traffic control devices, lighting conditions, and terrain and environment descriptions.

Performance of elderly citizens when driving has been studied though the use of instrumented vehicles and a driving simulator (Hakamies-Blomqvist, Henriksson, Lundberg et al. 2001). The studies have been conducted at the Swedish Road and Transport Research Institute in Linköping. 35 subjects, 21 men and 14 women, completed the driving tasks on a rural road. The route measured 9 km in the field as well as in the simulator, and the subjects made repeated runs on it. The result of the study proved that the test subjects drove broadly in the same way in both the simulator and the instrumented vehicle. In another driving simulator study conducted at the Swedish Road and Transport Research Institute, hypotheses regarding change of driver's speed choice and side acceleration caused by the design of sharp curves were tested by analysis of variance (Helmers and Tornros 2004). Six subjects drove several runs on a simulated rural road with a length of 5 km. The location of the rotation centre for banking of sharp curves was proved to influence driver's choice of speed. The results were not influenced by the amount of training the subjects had in the simulator.

Validation of speed driven on a route in the field and in a driving simulator was performed at the University of Central Florida and comprised 21 subjects (Klee, Bauer, Radwan et al. 1999). Of the original total of 30, 9 were not able to complete the study due to simulator sickness. Statistical analysis showed resemblance between speed data from the field and simulator runs at 10 out of 16 designated sites along the road.

Jonsson measured spot-speeds in several Swedish cities (Jonsson 2001; Jonsson 2005). The spot-speeds were measured with traditional radar guns placed out of sight of passing drivers. Manual counts of pedestrians and cyclists were carried out during the speed measurement time period. Considering that the measurement time period per site was approximately 15 minutes, the method implied swift data collection covering several sites per city.

Karlgren (2001) measured speed profiles from a point on a road by means of a laser speed meter. The measure gives a direct reading of the speed of each vehicle travelling on the observed stretch. The average speed and 85the percentile speed were calculated and plotted in a speed profile of the observed road. The speeds of free vehicles were measured from inside an ordinary car using a laser speed measure unit connected to a laptop PC. The laser speed unit registered the speed and distance of the passing car, following the car when entering the studied street link, passing the hump and leaving the link. The purpose of the study was to investigate the impact of speed humps on the speeds of passing cars.

Archer (2005) investigated methods for traffic safety analysis based on on-site observations and photometric measurements (video-analysis), and the potential of micro-simulation for safety and performance estimation.

When studying the safety impacts of speed cushions, Towliat (2001) made spot-speed measurements using a radar gun, and conducted car-following studies with specially equipped vehicles, and conflict studies. In addition, approximately 300 free cars were followed using a specially equipped vehicle in a subsequent study of traffic performance at speed cushions (Rezaie 2002). The cars that were followed were randomly chosen from the first free cars in a lane. The driver of the specially equipped vehicle coded the location, the number of intersections, and crossings, when the vehicle passed predetermined checkpoints. The driver followed the vehicle chosen, mimicking the driver’s behaviour as far as possible.

Besides the listed methods, the Swedish Road Administration regularly collects traffic spot data on traffic volume, vehicle types and speed. In 1999, data collection also included acceleration and retardation at randomly selected sites around Sweden (Stenbäck 2000). Statistical surveys of speed, headway and time gap have also been conducted by the SRA (Nilsson 2001). The locations of the measurements were selected using two independent probability samples. A random sample of road segments was selected, followed by a random sample of measurement sites within the road segment. The samples were drawn from state-owned roads and local authority roads. Data is available in the form of spot speeds, which are of interest to the present investigation, for example as references for speed levels on different types of street in the main road network. However, no detailed description exists of the traffic conditions that affected the speed observations or the traffic environment around the measurement locations. Data on the different street variables (carriageway width, lanes, reserved lanes, traffic control and regulation features, traffic on intersecting streets, and the surrounding environment) at the time the measurements was also collected to some degree

The American Travel Time Data Collection Handbook (Turner et al. 1998) and the earlier Swedish travel time data collection study (Bergh 1985), demonstrate data collection techniques called test vehicle and licence plate matching. Three test vehicle driving styles are common according to the American handbook: average car, floating car and maximum car. The test vehicles technique provides speed profile data of investigated routes. Collection of passage time and vehicle identity, at two of more crossing points, enables average travel times and speeds to be calculated.

2.3.3 Review of methods for speed modelling

A number of methods for speed modelling were developed and used in the Indonesian and Chinese Capacity Study (Bang, Ronggui, and Huichen 1998; Marler, Harahap, and Novara 1994). The collected empirical data built a foundation for analysis of speed and flow relationships and the estimation of passenger car equivalences (abbreviated pce) for all vehicle types. The studies comprised the following steps:

1. Multiple regression analysis of aggregated short-base data over a range of traffic flows.
2. Multiple regression analysis of separate flow classes based on short-base data.
3. Multiple regression analysis using aggregated travel time data from long-base studies.
4. Analysis of speed flow relationships produced by the VTI simulation model (Brodin, Carlsson, and Bolling 1982).

The existing speed models on urban roadways in the U.S. have been summarized by Wang, Dixon, Li and Hunter (2006) and are listed in table 2:1. The models are based on operating speed, which is defined as the speed at which drivers are observed operating their vehicles under free-flow conditions as defined in the AASTO Green Book 2001 (Fitzpatrick, Carlson, Brewer et al. 2003). The 85th percentile of the distribution of observed speeds is frequently used as a measure of the operating speed in the U.S. for design purposes. The majority of the speed models are empirical and based on spot speed measured at horizontal curves. Local roadway characteristics serve as the independent variables.

Table 2:1 Summary of operating speed models for urban conditions The speed unit is km/h for all models except Fitzpatrick et al. (2003). Source: Wang et al. (2006)

Speed prediction model	**Location**	**R2**
Fitzpatrick et al. (1997)		
$V85_{(1)} = 56.34 + 0.808R^{0.5} + 9.34/AD$	(1) Suburban arterial horizontal curves	0.72
$V85_{(2)} = 39.51 + 0.556IDS$	(2) Suburban arterial vertical curves	0.56
Fitzpatrick et al. (2001)		
$V85_{(1)} = 42.916 + 0.523PSL - 0.15DA + 4.402AD$	(1) Suburban arterial horizontal curves	0.71
$V85_{(2)} = 29.180 + 0.701PSL$	(2) Suburban arterial straight sections	0.53
Or without speed limits		
$V85_{(1)} = 44.538 + 9.238MED + 13.029Ll + 17.813L2 + 19.439L3$		0.52
$V85_{(2)} = 18.688 + 15.050W$		0.25
Bonneson (1999)		
$V85 = 63.5R\,(-B + \sqrt{(B^2 + 4C/127R)} \leq V_a$	Urban low speed, high speed roadways Rural low speed, high speed roadways Turning roadways	0.96
$C = E/100 + 0.256 + (B - 0.0022)V_a$		
$B = 0.0133 - 0.0074\, I_{TR}$		
Poe et al. (2000)	Low speed urban streets	
$V85_{(l)} = 49.59 + 0.50D - 0.35G + 0.74W - 0.74HR$	(1)150 ft before the beginning of curve	0.99
$V85_{(2)} = 51.13 - 0.10D - 0.24G - 0.01\,W - 0.57HR$	(2) beginning of curve	0.98
$V85_{(3)} = 48.82 - 0.14D - 0.75G - 0.12W - 0.12HR$	(3) middle of curve	0.90
$V85_{(4)} = 43.41 - 0.11D - O.12G + 1.07W + 0.30HR$	(4) end of curve	0.90
Fitzpatrick et al. (2003)		
$V85_{(l)} = 8.666 + 0.963PSL$ (miles/h)	(1) Suburban/urban arterial	0.86
$V85_{(2)} = 21.131 + 0.639PSL$ (miles/h)	(2) Suburban/urban collector	0.41
$V85_{(3)} = 10.315 + 0.776PSL$ (miles/h)	(3) Suburban/urban local	0.14
$V85_{(4)} = 36.453 + 0.517PSL$ (miles/h)	(4) Rural arterial	0.81
Tarris et al. (1996)	Low speed urban streets	
$V85_{(l)} = 53.5 - 0.265D$	(1) Aggregated speed data	0.82
$V85_{(2)} = 53.8 - 0.272D$	(2) Individual speed data	0.63
$V85_{(3)} = 52.2 - 0.231D$	(3) Panel analysis	0.80

Where

V85 = Estimated 85 percentile speed (km/h)
AD = Approach density (approaches per km)
D = Degree of curvature
DA = Deflection angle (deg)
IDS = Inferred design speed (km/h)
I_{TR} = Indicator variable (1.0 for turning roads, 0 otherwise)
HR = Hazard Rating (severity and frequency of roadside objects within 1.5 m of the travel way)
L1-3 = Roadside development. L1 school =1 otherwise 0,
L2 residential =1 otherwise 0, L3 Commercial =1 otherwise 0
MED = Median
PSL = Posted speed limit (km/h)
R = Curve radius (m)
Va = Approach speed (km/h)
W = Lane width (m)

The study of speed choice on low speed urban streets by (Tarris, Poe, Mason et al. 1996) describes the use of descriptive statistics obtained through data aggregation. According to the authors, descriptive statistics misleadingly reduce the total variability and the nature of the variability associated with the statistical relationships. When using them, the influence of geometric elements may be overstated or understated. Therefore, recording the speed profile of individual vehicles at the test segment and performing a panel analysis of this data is recommended. The procedure captures the individual driver effects and time effects in addition to geometric effects. Panel analyses are straightforward extensions of linear regression. According to the authors a panel data set is commonly used in econometric studies. The data set consists of multiple observations of a specified group at several points in time. The use of this modelling technique enables the unobserved variability of the group effects and time effects to be captured. These were then studied by cross-sectioning individual drivers as a group and to speed sensor location as a time period.

Wang et al. (2006) developed operating speed models for low speed urban street segments based on roadway alignment, cross-section characteristics, roadside features, and adjacent land uses. The model was computed from second-by-second in-vehicle GPS data from two hundred randomly selected vehicles in Atlanta, Georgia. Regression analysis was used to select the model variables. The formula for the final operating speed model in miles per hour and with an R2 value of 0.67 is as follows:

$$\begin{aligned}
V85^{th}\ (\text{mph}) = 31.56 &+ 6.49 \times \text{number of lanes} \\
&- 0.10 \times \text{number of roadside object per mile/offset (ft)} \\
&- 0.05 \times \text{number of driveways per mile} \\
&- 0.08 \times \text{number of intersections per mile} \\
&+ 3.01 \times \text{kerb indicator} \\
&- 4.26 \times \text{pavement indicator} \\
&- 3.19 \times \text{parking indicator} \\
&+ 3.31 \times \text{land use1} \\
&+ 3.27 \times \text{land use2}
\end{aligned} \tag{2.7}$$

Conclusions of the study were firstly that the number of lanes per direction of travel has the most significant influence on drivers' speed on urban streets. Variables such as kerbside parking, pavement presence, roadside object density and offset, T-intersection and driveway density, raised kerb, and adjacent land use were also significant.

Karlgren (2005) developed a speed model for nine streets in Gothenburg, Sweden, by use of multiple regression analysis. Observed mean speed for street segments was formulated as a function of the parameters average carriageway width, number of passing vehicles per hour in the current direction, number of parked vehicles per 100 metres, number of pedestrians and cyclists crossing the street per hour and 100 metres, and average width from pavement to nearest building or tree. A simplified model was developed and presented in equation 2.8. The R2 value was 0.69.

$$\begin{aligned}
V_{Seg.}\ (\text{km/h}) = 26.3 &+ 0.04 \times \text{vehicle flow per hour in the studied direction} \\
&+ 2.52 \times \text{average carriageway width (m)} \\
&- 0.05 \times \text{number of crossing pedestrians and cyclists} \\
&\qquad \text{per hour and 100 m}
\end{aligned} \tag{2.8}$$

2.3.4 Review of evaluation methods using microscopic simulation

The literature provides several methods to evaluate traffic performance of alternative road design, and for various traffic conditions. With steadily increasing computer speeds, the ability to reproduce successive changes in a traffic system over time by simulation has increased compared to analytical models (Burghout 2004). Space-time dynamics are a basis in the simulation models, and the levels of detail range from macroscopic to microscopic. The microscopic models aim to represent the entities, vehicles, in the traffic stream and their interactions with other road users. The measures speed, flow and density are a result of calculations of the microscopic models.

Eisele and Frawley (2005) estimated the impacts of access management scenarios through field data collection and micro simulation of traffic performance. The traffic performance parameters travel time, speed and delay were evaluated by traffic simulation of alternative street design. Levels of safety and performance at a suburban junction and vehicle actuated signal logic were evaluated by micro-simulation in a Swedish study (Archer 2005). In the Indonesian study, pce values and speed flow relationships were produced by traffic simulation with a range of traffic volumes (Bang et al. 1995).

2.4 INFLUENCE OF STREET DESIGN AND CONTROL CONDITIONS

A literature review of relationships between speed and design details is presented here. The section covers the effects on the speed of car traffic of the

- design of the carriageway,
- traffic flow,
- ratio of through traffic, and
- traffic environment.

2.4.1 Influence of the street design and environment – an overview

Several studies that describe the relationship between the design of *rural roads* and road users' choice of speed have been developed over the past few decades (Bang et al. 1995; Carlsson and Cedersund 1998; Carlsson and Yahya 1998; Swedish Road Administration 2001a). Significant relationships between the design of an *urban street* and road users' speed are more difficult to find in the literature. As regards the relationship between design and road users' behaviour, it is not just one particular detail of the design that determines road users' behaviour, but several different ones that interact and build a holistic picture in a more or less complex fashion (Linderholm 1996b). In the opinion of the author, this also makes it very difficult to find significant general relationships in an urban setting.

In a rural road environment, motorists are more often able to travel at free-flow speed. This is defined as the driver's choice of speed under given conditions (the road design, the speed limits in force, the vehicle's performance etc). On rural roads, free-flow speed is in general influenced by the alignment of the road (Fitzpatrick et al. 2000). A vehicle that is forced to adapt its speed to other vehicles becomes a restrained vehicle, leading to reduced speed at higher traffic flow (Swedish Road Administration 2001b). In a built-up environment, there are also other factors that influence a driver's choice of speed as discussed below. Another factor that may be of importance as regards speed is the street design, function, and roadside development (Ericsson 2000; Poe, Tarris, and Mason 1998).

A third factor affecting speed is what the driver remembers of the section just passed through and what he or she can see of the next section. The past alignment and the upcoming alignment have an influence on a driver's behaviour while driving on urban streets (Smoker, Tarris, and Mason 1996). Smoke, Tarris and Mason take a “zonal” approach, which recognizes that drivers do not choose their speed based merely on the influence of geometric and roadside elements at their exact location in the alignment. The properties of the alignment they have just passed (Smidfelt-Rosqvist 2003) and the alignment they see ahead of them have a significant influence on the actual speed chosen on urban streets.

Driving behaviour is also influenced by the aesthetic values of the traffic environment (Drottenborg 2003). The driver has a memory bank of different environments and the behaviour required in each (Nyberg, Thiseus, Englund et al. 1998).

Other factors that may influence speed choice include driving experience and driving style, perception of the risk of being involved in an accident or receiving a speeding ticket, the weather, and lighting conditions (Spolander, Laurell, Nilsson et al. 1979). Distractions within the vehicle also influence driving performance (Stutts et al. 2003) as do influence of fatigue, medication and drugs. Trip purpose influences the speed driven, i.e. if it is private or for a client.

Vehicle travel times and speed on Swedish streets and roads was collected, analysed and modelled in a national study in the mid eighties by the Swedish Road Administration (Bergh 1985). A speed model was developed for an arterial road, for which the collected data of average travel speed and other measures gave significant relationships with traffic flow, posted speed limit, road type and configuration, and environment type. Speed flow relationships have been developed continuously by the Swedish Road Administration. An update and validation of the speed flow relationships showed good similarity with measured speeds on rural roads; for urban streets, further collection of data was recommended (Carlsson and Yahya 1998).

2.4.2 Design of the carriageway

This section is arranged according to different types of traffic-related forms of design and control conditions.

Carriageway width

The relationship between carriageway width and free-flow speed is generally not strong (Amundsen and Christensen 1986; Bang et al. 1995; Gattis and Watts 1999). Figure 2:2 illustrates average light-vehicle speed on undivided roads and its relation to carriageway width. Vehicles’ speed on roads with a carriageway width of 7 metres ranged from 60 to 80 km/h. Vehicle speeds varied on average from 70 to 80 km/h on roads with carriageway widths of 8 metres or greater.

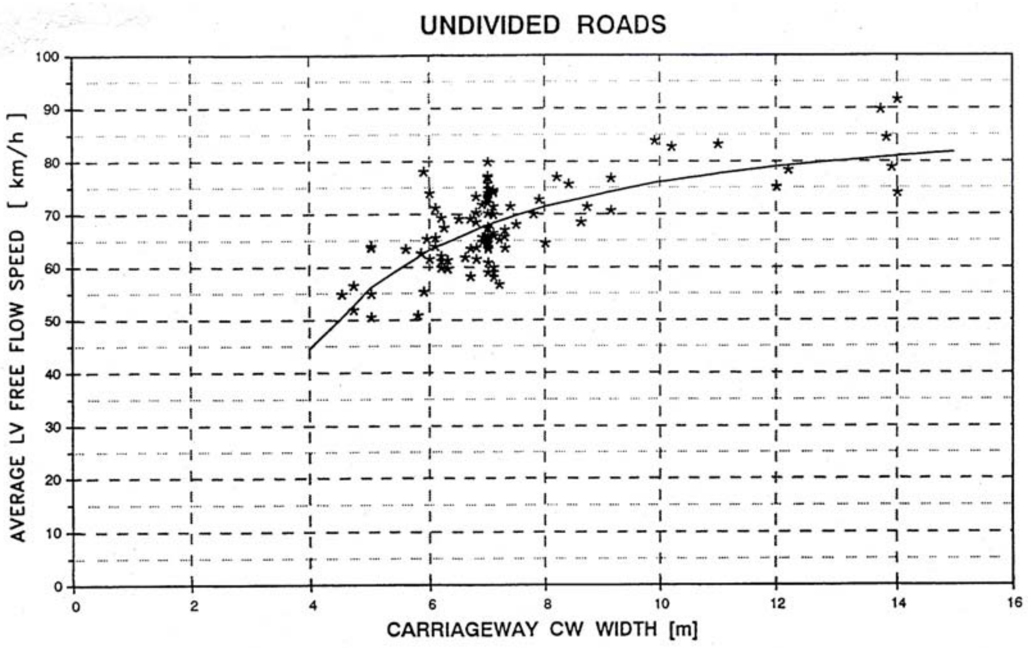


Figure 2:2 Relationship between carriageway width and free-flow speed, for light vehicles measured for undivided roads (Bang et al. 1995)

Gattis and Watts (1999) showed a weak relationship between the width of the street and the vehicles' speed. In the opinion of the authors, the purpose of the journey has a more significant impact, and they recommend that through traffic and local traffic be separated when measuring speed. On local streets, however, significant differences in average speed were noted between narrow streets and wide ones.

Traffic lanes

An American evaluation of the efficient use of street width (NCHRP 1990) emphasises the gains obtained by changing the carriageway layout on main streets. Adding a turning lane in the middle and narrowing the width of all the lanes considerably improves road safety and/or traffic performance. The desired width on main streets is 11-12 feet (3.35-3.66 m), but narrower traffic lanes might also have a positive effect on safety and performance. Lanes narrower than 10 feet (3.05 m), however, should be implemented with caution.

According to Linderholm (1996a), channelling turning traffic at intersections is of great importance for traffic performance. Increased traffic performance at intersections leads to increased traffic performance on the street.

Reserved lanes/space for different traffic types

A Swedish study showed that cyclists were more positive towards a street after the introduction of in-street bicycle lanes, and that amount of side by side cycling was reduced, as was cycling on pedestrian paths (Nilsson 2003). Cyclists had more space when car traffic was moved further from the kerb. The in-street bicycle lanes did not affect the speed of car traffic.

Reserving parts of the roadway for public transport reduces the space available for other traffic. St.Jacques and Levinson (1997) made the following general observations regarding the effects of bus lanes:

- If a mixed traffic lane is used mainly for bus traffic, and converted to bus lanes, the capacity lost by other traffic is relatively small. If, on the other hand, there is little bus traffic in the lane (i.e. less than 40 buses per hour), and the lane is reserved for bus traffic, the capacity lost by other traffic may be as much as between 30% and 50% of the capacity of a normal lane.

- If the lane closest to the kerb is converted into a bus lane all the way to the stop line at an intersection, the capacity available for other traffic is reduced by one whole lane. However, if the bus lane ends in good time before the stop line and other traffic can make a right turn at the intersection, capacity loss is less than one lane.

Space for parking and stopping

The Norwegian Road Safety Handbook (Elvik, Borger-Mysen, and Vaa 1997) illustrates the advantages and disadvantages of kerbside parking. Prohibiting street parking can mean a higher level of service for commercial traffic and operation and maintenance vehicles. Kerbside parking in residential areas can be used to narrow a segment of the street and thus restrict vehicles' progress (Giese, Davis, and Sykes 1997). The disadvantage of using parked cars to narrow a street segment is that parking reduces traffic safety. Children who want to cross the street are hidden behind the parked vehicles. The HCM2000 (Transportation Research Board 2000) considers the influence of kerbside parking only in the case of saturated flow at a signalised intersection (Chapter 16).

Central refuges, separators and medians

Speed-flow relationships on various types of rural roads have been studied by, for example, Bang (1995) and the Swedish Road Administration (2001b). Roads with directional divided carriageways maintain greater average vehicle speeds than undivided roads, provided that the carriageway contains a lane for overtaking. This is exemplified in Figure 2:3, which illustrates the speed-flow relationships of Swedish 4, 3 and 2-lane rural roads. The posted speed limits are 110 and 90 km/h.

A new road type has been developed and built in Sweden over the past ten years. It is called the 2+1 road. It has a carriageway width of 13 metres, directional divided carriageways separated by a wire barrier, alternating 2 lanes in one direction and one lane in the other direction of travel. The design does not permit overtaking of vehicles in the one-lane direction and vehicle speeds on this road type are lower than other road types. The average speed on 4-lane motorways is greater than the speed on 4-lane highways divided with wire barrier separator.

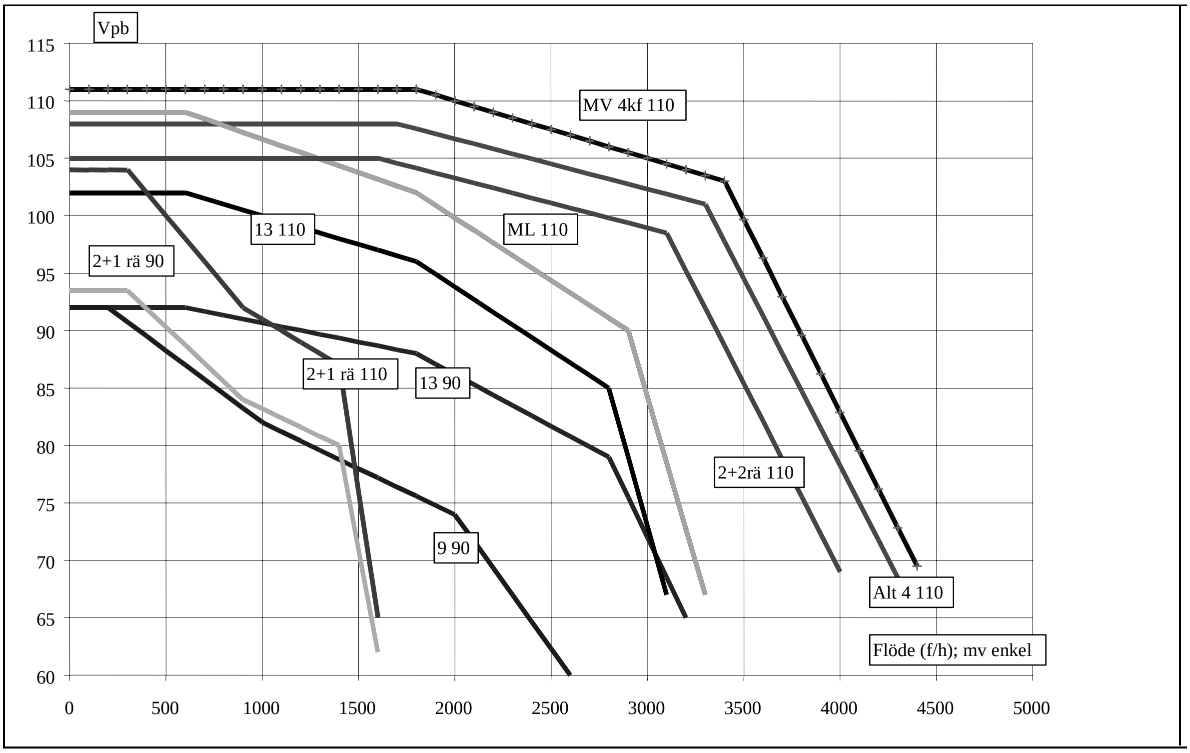


Figure 2:3 Speed-flow relationship for various types of Swedish rural roads. Source Swedish Road Administration (2001b).

The y-axis represents the speed of automobiles. Vehicle flows per hour are shown along the x-axis; two-way flows for all road types except the motorway, for which one-way flow was measured. The abbreviation in the figure of road types and posted speed limits, are explained as follows;

MV 4kf 110	Motorway, 4 lanes divided, 110 km/h
Alt 4 110	Highway, 4 lanes undivided,110 km/h
ML 110	Highway, 2 lanes undivided, 110 km/h
13 110	Highway, 2 lanes undivided, 13 metres carriageway width, 110 km/h
13 90	Highway, 2 lanes undivided,13 metres carriageway width, 90 km/h
9 90	Highway, 2 lanes undivided, 9 metres carriageway width, 90km/h
2+2 rä 110	Highway, 4 lanes divided by a wire barrier, 110 km/h
2+1 rä 110	Highway, 3 lanes divided by a wire barrier, 110 km/h
2+1 rä 90	Highway, 3 lanes divided by a wire barrier, 90 km/h

Special devices for reducing speed

Special devices for reducing speed include speed humps, horizontal deflections, short narrow segments, segregating the street environment, narrowing the carriageway, pedestrian crossings raised above the level of the carriageway, giving streets environmental and road safety priority, and turning main streets into traffic-calmed streets (Brandberg et al. 1999).

Giving a street environmental and road safety priority leads to a reduction in speed for through traffic (Elvik et al. 1997). The street is designed so that through traffic road users understand that the street is primarily intended for local traffic and that through traffic is subject to the conditions of the local traffic. This is achieved by e.g. narrow segments, horizontal deflection, separated pedestrian and bike traffic lanes, roundabouts etc. Waiting times for traffic intersecting and joining such a traffic-calmed distributor road are somewhat shorter due to the lower traffic tempo. Linderholm (1996a) quotes examples where the average speed on a traffic-calmed distributor road has fallen from about 50-60 km/h to 35-40 km/h.

On a so-called walking-pace street, all road users use the same carriageway and the maximum permitted speed is walking pace (Brandberg et al. 1999). Reconstructing a main street into a walking-pace street reduces the level of service for car traffic, commercial traffic and operating and maintenance traffic, but increases the level of service for other road users (Elvik et al. 1997). The speed reduction for motor traffic was in the order of 15-25 km/h.

Humps are a very effective way of reducing speed (Linderholm 1996a). The so-called Watts hump reduces speed to a level somewhere between 20 and 25 km/h, regardless of the types of vehicles and how fast they drove before the hump was built. Platform humps reduce speed somewhat more. For traffic calming purposes on a street link, it is of interest to build more than one speed hump. The relationship between the distance between humps and the resulting average speed has been modelled in a Swedish study (Karlgren 2001). An example of collected vehicle speed data when traversing a street equipped with two speed reducing means is illustrated in Figure 2:4. Using the speed predicting models presented in the study, the highest mean speed between two humps can be calculated from the following formula: the lowest average speed at either hump + 2.25 + (0.11$\times$ the distance between the humps) in km/h. The highest speed based solely on the distance between the humps is calculated using the formula 16.6 + (0.18$\times$the distance between the humps) in km/h.

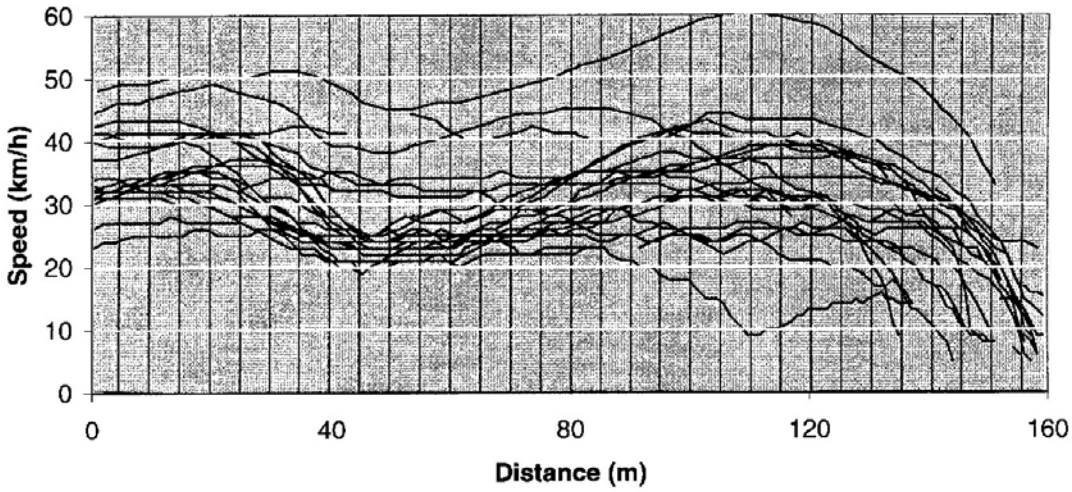


Figure 2:4 Example of speed profiles of vehicles traversing a street equipped with a raised intersection and a hump. Source (Karlgren 2001).

The effects of road cushions have been evaluated at Lund Institute of Technology (Towliat 2001). A road cushion is a type of hump that does not extend across the width of the street. A cushion is built approximately 8 cm above the surface of the carriageway and the platform is 1.2 to 2.0 metres wide by 2.0 to 36 metres long. The cushion is placed about one car length in front of the pedestrian crossing. Refuges are built alongside the speed cushion, partly to prevent drivers trying to drive round the obstacle. The study showed that the speed of car traffic was lower after the speed cushions were built. The before study reported that car and city bus speeds, on the 85th percentile level, at the sites varied from 49 to 60 km/h. The afters study proved speeds, on the 85th percentile level, fell *to* between 26-34 km/h, and speeds were approximately the same right before passage over the cushion. Vehicle speeds, on the 85-percentile level, fell to between 21 and 31 km/h on the actual pedestrian crossing.

Horizontal deflection of the carriageway and narrowing the street also reduce vehicle speed. The speed at a one-sided deflection, measuring almost one lane width, of a carriageway is reported by Linderholm (1996a) to drop from 40-50 km/h to 30-40 km km/h given unchanged traffic flow.

Exits from premises
A large number of exits along a street reduce speeds according to the Norwegian Road Safety Handbook (Elvik et al. 1997). The authors describe a Norwegian study from the 1980s (Sakshaug 1986), that showed that when the number of exits was increased by ten every 500 metres, the average speed on the street fell by 1.0 km/h where the posted speed was 50 km/h. A conclusion from studies in Indonesia was that side-friction events, including vehicle entries and exits from roadside properties and minor roads, have a substantial influence on free-flow speed and capacity (Bang et al. 1995). The impact of vehicle entries and exits had a high weight in the side-friction equation, which is further explained in section 2.5.2.

Traffic devices
See section 2.5.2 for a description of the influence of pedestrian crossings on the speed of car traffic.

Traffic regulation
This refers to traffic regulation measures in the form of posted speed limits and the prohibition of parking and stopping.

The posted speed limit influences vehicle speed on major urban roads significantly, which is verified by Fitzpatrick et al. (2001) and (2003), see Table 2:1.

The effects of substantially altered posted speed limits on roads in the Norwegian main road network have been studied from the point of view of speed and safety (Sakshaug 1986). The results of the study showed that the average speed fell by between 3 and 4 km/h for every 10-km/h reduction of the speed limit. Conversely, the average speed increased by the same amount when the speed limit was raised by 10 km/h.

Prohibiting parking and/or stopping on a city centre street improves the level of service for commercial traffic and operation and maintenance work (Elvik et al. 1997). It also leads to a higher level of service for all the traffic using the street, which the result that average speed increases. Elvik, Mysen et al. refer to an older American study by Crossette and Allen, where measured speeds increased from between 30 and 45 km/h before parking was prohibited to between 40 and 60 km/h after.

If a street or road is given right of way so that traffic on all connecting streets have to give way, the average speed on the major road will increase by 2-3 km/h reports Elvik et al. (1997). The value is based on several recent Norwegian studies.

2.4.3 Traffic flow

In addition to the physical design and interactions with other road users, the speed at which a driver can travel on a section is dependent upon the traffic flow. At times of low traffic flow, free-flow speed can normally be maintained and performance is good. As the traffic flow increases, there is less possibility for drivers to drive at free-flow speed and the other vehicles' rhythm affects the individual driver's speed (Transportation Research Board 2000). Researchers at VTI studied relationships between speed and flows measured on rural roads (Carlsson and Yahya 1998). The study was part of the evaluation and improvement of the Swedish Road Administration's model for estimation of travel times of alternative road link designs. As regards speed-flow relationships on streets in built-up areas, the researchers suggest continued studies of speeds in built-up areas and of various street design and traffic conditions.

One of the aspects investigated in the project on urban driving patterns was a "spillover" effect on driving patterns between current and preceding street types (Smidfelt-Rosqvist 2003). This spillover effect was highly significant for most studied driving pattern characteristics, including average speed. Looking at the parameter *average speed*, 6 % of the current average speed was carried over from the preceding section.

2.4.4 Ratio of through traffic

The purpose of the journey is of great importance for the speed at which the individual drivers drive their vehicles and should be included as a variable in a study of effect relationships (Amundsen and Christensen 1986; Gattis and Watts 1999). Evidence that bears this out can be found in a study of through traffic speed on a street before and after conversion to a traffic-calmed street (Elvik et al. 1997). The study showed that through traffic speed was reduced after the street was rebuilt.

2.4.5 Traffic environment

According to a U.S. study, the street's design and environment and individual driving behaviour are decisive for a driver's speed choice (Tarris et al. 1996).

A road user's behaviour can be described in terms of the way in which an individual controls his or her behaviour (Nyberg et al. 1998): this has its origins in the levels defined by Rasmussen in Information Processing and Human-Machine Interaction, presented in 1986. Which level a person uses is determined by the experience he or she has of the task to be performed. According to Rasmussen, the psychological levels for decision-making are as follows:

- A knowledge-based level (the car driver's action is preceded by a conscious decision; this applies primarily to inexperienced drivers or drivers in unaccustomed situations).
- A rule-based level (the driver has built up extensive experience and can act unconsciously).
- A proficiency-based level (automatic behaviour that requires little awareness on the part of the driver).

According to Rasmussen's findings, most drivers alternate between all three levels. Inexperienced drivers need to use the knowledge-based level to a greater degree than experienced drivers.

The road users' mental representation of the traffic system has been studied by Nyberg et al. (1998), with the aim of determining whether this mental representation differs between inexperienced and experienced drivers. The subjects of the experiment were asked, among other things, to state what posted speed they thought applied in different road environments. The results showed that both inexperienced and experienced drivers had an inner model of the posted speed limit that applied that corresponded well with the actual posted speed.

Road users' behaviour can be also divided into different types of task (Pettersson, Harms, and Helmers 1992), which, according to Rasmussen's work in 1986, are

- a strategic level (choice of car and domicile, travel plans)
- a tactical level (interaction with traffic), and
- an operative level (vehicle control).

Pettersson, Harms et al. state that "human beings use their environment actively and rationally, consciously and unconsciously in order to be able to act in any situation in such a way that their goals are achieved and their needs satisfied". It is therefore important that "we try to create vehicles and road environments that give road users a direct perception in all situations of what is rational traffic behaviour, and that this behaviour corresponds with the desired traffic behaviour." The individual's perception of the road, the environment around it, what happens on it and the experience of the individual are closely related to selection of free-flow speed.

The aesthetic values of the traffic environment affect driving style (Drottenborg 2003). The hypothesis was supported by two research methods: i) by directly relating driving speed to aesthetics, and ii) through the use of the employed model of driving behaviour as a function of the basic emotional process. The first method showed lower speeds in terms of maximum speed, the 85th percentile and speed oscillations, when driving in beautiful environments as compared to environments perceived as ugly. The next method showed that when aesthetics improved, drivers' mood became more positive during a stopover, which resulted in a lower speed after the stopover. The influence had a value of between 5% and 10%.

2.5 INFLUENCE OF INTERACTION WITH OTHER ROAD USERS

2.5.1 General

Travel on the main road network in a built-up area involves meeting and interacting with other road users. This is particularly true during peak traffic periods. Irrespective of when a movement takes place, situations will arise when a road user must interact with other road users which may imply a modified pace of travel, increased or decreased, or change of travel course. This section describes the effects of interactions with public transport vehicles, cyclists, and pedestrians on driving patterns and traffic performance.

The road environment is complex and usually contains several factors that have an impact on road users' choice of speed and travelling time as well as the system's accessibility to different categories of road user. Speed choice is also influenced by interaction with other types of traffic (Marler et al. 1994). Examples of events that influence car drivers' speed choice include

- vehicles driving in the same lane or adjacent lanes

- traffic from the opposite direction intruding into one's own lane or blocking overtaking manoeuvres
- buses arriving at or leaving bus stops or reserved lanes
- cyclists and moped riders sharing the same carriageway (mixed traffic)
- pedestrians and cyclists crossing the street or walking along it
- stopping or parked vehicles in the kerb lane.

2.5.2 Interaction with pedestrians and cyclists

In 2000 a law was introduced in Sweden forcing drivers to give way to pedestrians at uncontrolled pedestrian crossings. Waiting times for these two categories of road user were studied before and after the law came into effect (Thulin and Obrenovic 2001). The ratio of cars that stopped or visibly slowed down to allow pedestrians to cross was investigated. The study covered waiting time per waiting car in relation to the number of pedestrians per hour, which increased on average by slightly over one second. The findings of the study were as follows:

- The ratio of pedestrians for whom motorists did not give way decreased on average from 52% before the new law to 31% after.
- The ratio of pedestrians to whom motorists did not give way, especially after May 2000, was lower at sites with a pedestrian traffic island compared to sites without traffic islands.
- The ratio of cars giving right of way to pedestrians had a strong relationship with the pedestrian traffic flow.
- The ratio of cars that stopped to allow pedestrians to cross increased; from 20 to 50% after the law was introduced.

This last effect is also supported by the findings in a study of the effects of road cushions (Towliat 2001), where traffic behaviour was studied at pedestrian crossings with road cushions and narrowed carriageway width. The speed cushions at all 17 experimental sites were located adjacent to a pedestrian or bicycle crossing and 5 metres in front of the crossing. Vehicles' speeds and other data were measured in a before-study, 1997, and in two after-studies in 1998 and 1999. The data was thus collected before the introduction of the law giving right-of-way to pedestrians at uncontrolled pedestrian crossings. The following results were obtained:

- Drivers' speeds decreased significantly during passage over the speed cushions at the experimental sites, and the speed was lowest right before the speed cushion. Drivers' speed behaviour during passage over the speed cushions did not change over time.

- The presence of a pedestrian or cyclist at the crossing did not cause drivers to reduce speed.

- Pedestrians and cyclists were more often given priority at the experimental sites and the increase was significant. Drivers' give-way behaviour improved significantly over time.

- Drivers' give-way behaviour was significantly the same towards pedestrians and cyclists before the introduction of physical measures at the sites. After introducing the measures, drivers' give-way behaviour improved significantly, particularly as regards cyclists.

The studies also showed that drivers' with lower speed were more likely to give way to pedestrians and cyclists. Another factor that affected drivers' give-way behaviour was the flow of pedestrian and cyclists. The greater the number of pedestrians and cyclists at a pedestrian crossing on an arterial road, the greater the likelihood that the driver would give way to them.

In 1995, before the law on pedestrians' right of way on uncontrolled pedestrian crossings, car speed profiles were registered at pedestrian crossing on a suburban street (Várhelyi 1996). The data showed that when no pedestrians were present, cars' average speed was over 52 km/h at the crossing. When a pedestrian was present on one side of the crossing, and about to use it, the cars drove over it at an average speed of 50 km/h. Three out of four motorists maintained or increased their speed as they approached the crossing in order to deter the pedestrian from claiming right of way. The desirable situation would be for a motorist to brake between 70 and 30 metres before the crossing in order to give the pedestrian right of way. In cases where pedestrians were present on both sides of the street, and about to use the crossing, the average speed of the cars fell to approximately 50 km/h some ten metres before the crossing and 47 km/h as they drove over it.

In a study conducted in England, average vehicle delay was measured for drivers at different types of pedestrian crossing (Hunt 1990). The average vehicle delay on street with a vehicle flow under 1000 vehicles/hour varied from 0.5 to 4 seconds depending on the crossing type. With increasing vehicle flow, the average vehicle delay increase exponentially at the pedestrian crossing type Zebra and signalised. The effect of speed cushions and narrowing the carriageway at pedestrian crossings on delay and travelling time has been analysed (Rezaie 2002). The average vehicle delay on the main road increased from 7.3 to 10.2 seconds at the free-standing pedestrian crossings after installation of speed cushions and narrowing of the carriageway. At intersections equipped with these measures, the average vehicle delay on the main road increased from 6.4 to 11.5 seconds.

Activity at the side of the road influences vehicle speed because the driver adapts his or her preparedness to brake in anticipation of a possible conflict accordingly. This phenomenon was studied in detail during the preparation of the Indonesian Highway Capacity Manual (Bang et al. 1995; Bang 1997) and the Chinese Highway Capacity Study (Bang et al. 1998). It was called side friction and defined in the Indonesian Manual as the "impact on traffic performance from roadside activities such as pedestrians, stops made by public transit and other vehicles, vehicles entering and exiting roadside premises, and slow-moving vehicles". An aggregate measure called FRIC was calculated using the relative weight of each type of event on vehicle speed:

$$FRIC = 0.6 \times PED + 0.8 \times PSV + 1.0 \times EEV + 0.4 \times SMV \qquad (2.9)$$

where:

FRIC	=	Side friction
PED	=	Number of pedestrians, walking along or crossing the road.
PSV	=	Number of stops made by small public transport vehicles (motorised as well as non-motorised) and the number of parking manoeuvres.
EEV	=	Number of motor vehicle entries and exits into and out of roadside properties and side roads.

SMV = Number of slow-moving vehicles (bicycle, trishaw, horse cart, ox cart, etc).

The FRIC parameter was shown to have a significant influence on capacity and vehicle speed. FRIC ranged from very low (below 50) to very high (over 350). The width of the shoulder also proved to influence the impact of side friction. Where side friction was very high and the shoulder narrower than 1.0 metres, free-flow speed was reduced by 16 km/h. The speed reduction was less for different combinations of wider shoulder and less side friction.

The following model for free-flow speed is presented in the Indonesian Highway Capacity Manual (Bang 1997).

$$FV = (FV_0 + FFV_W) \times FFV_{SF} \times FFV_{RC} \qquad (2.10)$$

where

FV = free-flow speed for actual conditions (km/h)
FV_0 = base free-flow speed for predetermined standard (ideal) conditions (km/h)
FFV_W = adjustment for effective carriageway width
FFV_{SF} = adjustment for side friction
FFV_{RC} = adjustment for road function class and land use

The Chinese and Indonesian capacity studies comprised multiple regression analysis based on short-base traffic data. The results of the analysis of two-way undivided Chinese interurban roads were

- the impact of traffic flow and carriageway was generally low
- the impact of shoulder width was insignificant.
- the influence of side friction and roadside development on the observed average speed was substantial.

The R2 values were generally rather low, below 0.6. The general equation used was:

$$V_{obs.} = Constant + a\times Q + b\times CW + c\times SW + d\times RSDEV + e\times FRIC + f\times MED \qquad (2.11)$$

where

V_{obs} = Observed average vehicle speed (km/h)
Q = Observed average traffic flow expressed in pcu/5min
CW = Carriageway width (m)
SW = Average total shoulder width per direction of travel
RSDEV = Average roadside development (% strip development)
FRIC = Weighted sum of observed side-friction events
MED = Existence of median (1=yes, 0=no)
a,b,c,d,e,f, = Regression coefficients

2.5.3 Interaction with public transport

In a built-up area, public transport may travel in mixed traffic or in reserved bus lanes. The degree to which it influences the speed of other vehicle traffic in a street section is partly dependent upon the number of public transport vehicles, the design of the stops and dwell time at the stops. The impact of a bus on overall vehicle capacity of the lane can be calculated using a passenger vehicle equivalent of 2.0 (Kittelson & Associates, Institute, and Limited 1999; St.Jacques and Levinson 1997). If it is a question of significant bus flows and buses overtaking other buses the reference number of passenger vehicle equivalent increases to 3.0 or 4.0 or more.

2.6 GENDER ASPECTS OF DRIVER BEHAVIOUR

A Norwegian study investigated drivers' reasons for speed choice by use of a qualitative method (Berge and Vaa 2003). The analysis of focus group sessions proved that drivers' speed choices are related to the physical design of the road, interaction with other road users, attitudes to speed limits in force and reasons linked to respect for the law. Driving with passengers in the car, particularly children, influence drivers to choose a lower pace compared to driving alone, except for some young drivers who reported speeding when driving friends. Several drivers expressed difficulties in maintaining a speed below the posted speed limit on rural roads. The sensation of speed was acknowledged during the focus group sessions, and more so by the female participants than male ones. A study by Forward, Linderholm, and Järkmark (1998) indicated that differences in female and male driving stiles have diminished over time, and that attitudes and self reported behaviour of women are becoming increasingly similar to those of men.

The consequence of speeding, such as increased accident risk, was given little consideration by the participants in the Norwegian study referred to above, which troubled the authors. An American national survey showed similar attitudes (Royal 2004). Many drivers are in favour of raised speed limits on rural roads, and yet admit that they would drive faster than the increased posted speed limit. At the same time, two thirds of drivers perceive other drivers' speeding to be a major threat to their own personal safety.

Women and men's valuation of the road system was examined in a Swedish study through interviews and questionnaires (Polk 2005). Regarding road type preferences, the impact of gender proved to be small but significant. Women had a preference for a variety of road types, while men preferred roads with a high level of service to a greater extent than women did. A large difference shown in the study was what drivers experienced while driving. In general, women expressed more concern for safety while men pronounced a dislike of obstructed travel. Women more often feel stress and irritation caused by drivers who exceed posted speed limits or drive very close to the rear of the subject's vehicle than men do. Drivers who drive slower than the posted speed limit were equally annoying to female and male subjects.

What drivers experience while driving has also been investigated in a Swedish study on driver interaction (Björklund 2005). Driver irritation and aggressive behaviour was measured. The results of the study proved that what causes most irritation is drivers who drive very close to the rear of the subject's vehicle. Over half the subjects reported that they would get very irritated or extremely irritated. The event brought forth aggressive reactions from 38% of the drivers, and the most common reaction was flashing the braking lights. A second item generating irritation was the parking situation where a fellow driver cuts in and takes the subjects planned parking spot. Driving close to the rear of the vehicle ahead may raise the probability of collision. The attributes of drivers involved in rear-end crashes were reported in an American study (Singh 2003). Analysis of the national databases on rear-end accidents proved age and gender to be significant. Young men and young women, 18 to 24 years, were more likely than older drivers to be involved in rear-end crashes. Comparing gender, young male drivers had 1.5 times higher likelihood of involvement in the striking vehicle role than young female drivers. For the struck vehicle role, young males and females had about the same likelihood of involvement.

The role of driver inattention in collisions has been investigated in an American study of accidents (Stutts, Rodgman, Reinfurt et al. 2001). The caused of distraction were the same for men and women, and they ranked from disturbance from outside person/object/event (30%), adjusting radio/cassette/CD (12%), other occupant (11%) and so forth. Gender differences in crashes involving driver distraction were small and insignificant.

The relationships between urban driving patterns, vehicle emissions and network characteristics have been studied in the cities of Lund and Västerås in Sweden (Ericsson 2000). Data on variations in driving patterns, i.e. speed and acceleration profiles, was collected to test and design a model for the relation between driving pattern factors and different outside circumstances. The study proved that the main impact on driving patterns was the factor of street type, which was defined by area type, street function and posted speed limit. Driver characteristics were also found to significantly affect driving patterns. Firstly, elderly drivers drove more slowly than drivers in other age groups. Secondly, female drivers were found to drive at lower average speeds than men did. The difference was in general 8-12 km/h slower depending on street type. In addition, female drivers tended to use less power when accelerating.

Driver and vehicle data collected in a study of operating speeds on American streets (Poe, Tarris, and Mason 1996) indicated small differences in mean speed among the stratified groups. Descriptive statistics on gender proved that the mean speed of male drivers was 2 km/h lower than that for female drivers. Very little difference in mean speeds was observed between the age groups (teens, young adults, middle adults and senior drivers), and the greatest difference in mean speeds, 4 km/h, was observed between senior drivers and teens. The difference in mean speeds comparing the age groups middle adults and senior drivers was insignificant. Statistical analysis of vehicle speed and number of passengers in the vehicle indicated a minor difference in mean speeds. The largest difference in mean speed (6 km/h) was observed between vehicles with four or more passengers and vehicles with no passengers. An insignificant difference in mean speeds between vehicles with two, three and four passengers were observed. A final part of the project was to model operating speed, based on the previous analysis. The best regression model proved road alignment, cross section, and roadside variables to explain the speed variation. The variables driver and vehicle characteristic explained two percent of the speed variation; it may, however, according to Poe, Tarris and Mason be due to data collection errors.

2.7 CONCLUSIONS FROM THE LITERATURE REVIEW

2.7.1 General

The studies reported and commented upon above indicate that relationships of a general nature exist between speed, street design and environment (land use/streetside development) and driver behaviour. Precise details of the extent to which these factors influence speed choice and performance for Swedish urban conditions were not found in the literature. However, several main factors were identified as having a potentially significant impact on driver speed choice on urban streets and are of great relevance for closer investigation. The factors were:

1. Geometric design (horizontal and vertical alignment; cross section)
2. Street type and function (arterial, distributor, local)
3. Posted speed limit
4. Urban environment type (CBD, residential, industrial)
5. Interaction with unprotected road users (pedestrians, cyclists) observed as the number of pedestrians/cyclists encountered per section of road.
6. Parked vehicles and parking manoeuvres (including bus stops)
7. Entries/exits from minor roads and roadside premises
8. Traffic flow (intensity, directional distribution, rate of through traffic)

Factors 5 to 7, called side-friction events, were given special consideration in the present study, since they are not included in the U.S. HCM Chapter 15 Urban Streets, (Transportation Research Board 2000) or in the corresponding Swedish Impact Assessment Catalogue (Swedish Road Administration 2001a).

2.7.2 Methods suitable for data collection, analysis and speed modelling

The reviewed literature showed a range of methods for data collection, analysis and modelling relevant to the present study. A number of methods were suitable for fulfilment of the objectives of this study, namely to improve the knowledge of factors that influence a driver's choice of speed and speed profile. Two modes of investigation were identified for improving this knowledge; micro study of individual driver speed behaviour and macro study of behaviour of a driver population. The micro study comprised data collection of speed profiles and driver behaviour. The data, if incorporated into a microscopic traffic simulation model, can be utilized for production of speed-flow relationships for a variety of urban conditions. The macro study investigated speed behaviour of a population of drivers at the link level. Speed and flow data, combined with street site variables, can be analysed by using multiple regression techniques with speed as the dependent variable.

The substance of methods used in the reviewed studies, and their relevance for the present study is outlined below.

The method of performing ***field studies to collect speed profile data of individual drivers (micro study)*** by use of specially equipped vehicles was performed by

- Fitzpatrick et al. (2000)
- Wang et al. (2006)
- Ericsson (2000)

The methods of data collection developed by Fitzpatrick et al. and Wang et al. are relevant to the present study due to the influence of side friction, street design and land use on speed. The video-analysis method developed by Archer (2005) has, if further elaborated, a potential to collect speed profile data. The data collection method developed by Ericsson has a potential to capture field data in a bottom-up approach, which is the focus of the present study, if supplemented with detailed descriptions of the traffic conditions that affected the speed observations.

The method of performing ***driver simulator studies to collect speed profile data of individual drivers (micro study)*** was performed by Hakamies-Blomqvist et al. and Klee et al.. This method of speed data collection is relevant to the present study due to the way it captures the factors influencing drivers' speed choice while travelling on urban streets and specifically the combination effects of the factors design, environment and the activity on the street.

The method of collecting ***speed data of a driver population (macro study)*** was performed by

- Bang, Carlsson and Palgunadi (1995)
- Swedish Road Administration
- Karlgren (2001) (mostly speed profiles)
- Towliat (2001)
- Jonsson (2005)

The method is of interest to the present investigation if supplemented with detailed descriptions of the traffic conditions that affected the speed observations (amount of side-friction etc), the traffic environment around the measurement location, and street variables (carriageway width, lanes, reserved lanes, traffic control and regulation features, traffic on intersecting streets, and the surrounding environment). These detailed descriptions were performed for example in the studies by Bang et al. and Jonsson.

The ***analysis method*** of regression techniques used by Bang et al. and Wang et al. is relevant to the present study due to the influence of side friction, street design and land use on speed.

Conclusions of the review of ***methods for speed modelling*** in the present study are firstly descriptive statistics, commonly used for the analysis of the short-base studies, the mobile studies and gender studies, for the purpose of identifying the speed impact of separated side-friction factors and gender differences in driver behaviour. Secondly, multiple regression analysis including all factors influencing a driver's speed is suitable to apply for the short-base data, long-base data, and the driving simulator generated data.

2.7.3 Male and female driver behaviour

The attitudes of women and their driver behaviour are increasingly similar to those of men (Forward, Linderholm, and Järmark 1998; Polk 2005; Stutts et al. 2001). A qualitative study of driver irritation and aggressive behaviour (Björklund 2005) proved that driving very close to the rear of the subject's car caused most irritation. Women more often experience stress from this event than men. Young drivers are more likely than older drivers to be involved in rear-end crashes, and young males more so than young females (Singh 2003). A study of speed patterns (Ericsson 2000) showed higher average speed for male than for female subjects. An American study of spot speed and a regression model of speed proved that male mean speed was lower than female (Poe et al. 1996). Furthermore, it was shown that road design factors best explained the speed variation. Driver variables such as age and gender merely explained a few percent of the speed variation. In conclusion, three groups of variables were found in the literature to be of interest for further examination when analysing gender issues and driving speed; average free-flow speed choice, speed profiles and driver behaviour in restrained traffic flow.

3. RESEARCH METHODOLOGY

This chapter contains an overview of the research methodology and documents, the methodology determination of data needs, collection and reduction of data, and the methodology for data analysis.

3.1 OVERVIEW

Transportation models are often characterized as being macroscopic, mesoscopic or microscopic. Macroscopic models normally conceptualise traffic streams on a link and node level, while mesoscopic models handle integer numbers of vehicles in groups called clusters or packets. Microscopic models normally capture driver behaviour parameters for individual vehicle movement, including interaction between vehicles (Merritt 2003).

The objectives of the study were realized by applying two modes of investigation:
- Micro study of individual driver speed behaviour.
- Macro study of traffic characteristics at the link level.

The micro study entailed a bottom-up approach to the research problem. The empirical data, of individual driver behaviour, enabled microscopic simulation calibration and modelling. Microscopic traffic modelling was applied for one street type in order to investigate the usefulness of this methodology in a wider traffic planning perspective. The macro study investigated traffic characteristics at the link level. Speed and flow data, combined with street site variables, was analysed by using multiple regression with speed as the dependent variable. Finally, a synthesis of speed models was performed based on the micro and macro studies. The overall research strategy is illustrated in Figure 3:1.

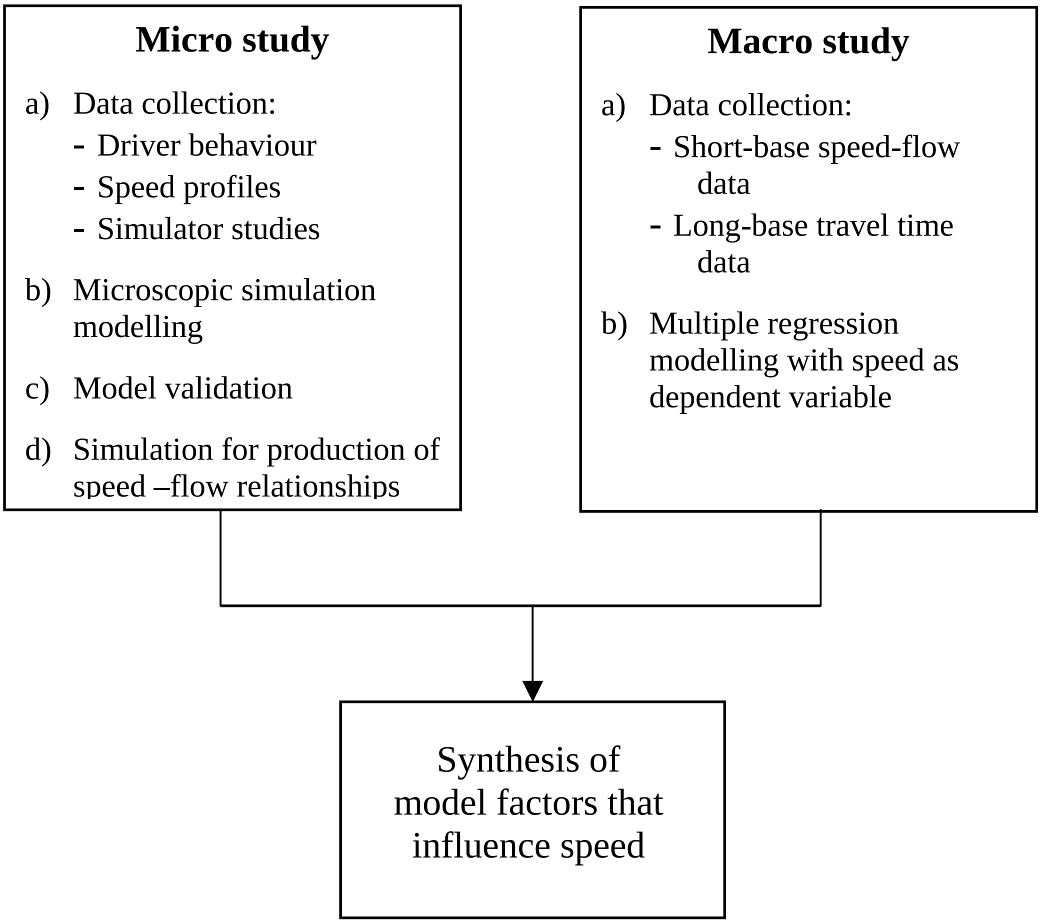


Figure 3:1 Overview of selected research methodology for development of urban speed models.

A speed profile of a vehicle travelling along a street, the spot-speed measured at two short-base stations and the average travel speed are illustrated in Figure 3:2. The speed profile represents the individual driver speed behaviour when travelling on the route. At the short-base stations, speed and flow data was collected for a population of drivers' from which space mean speed can be computed. The average travel speed for identified vehicles was calculated from the passage times at the entry to and exit from the studied link. Spot-speed measurements represent the speed at the specific survey location, while speed profiles capture the driver speed behaviour along the link.

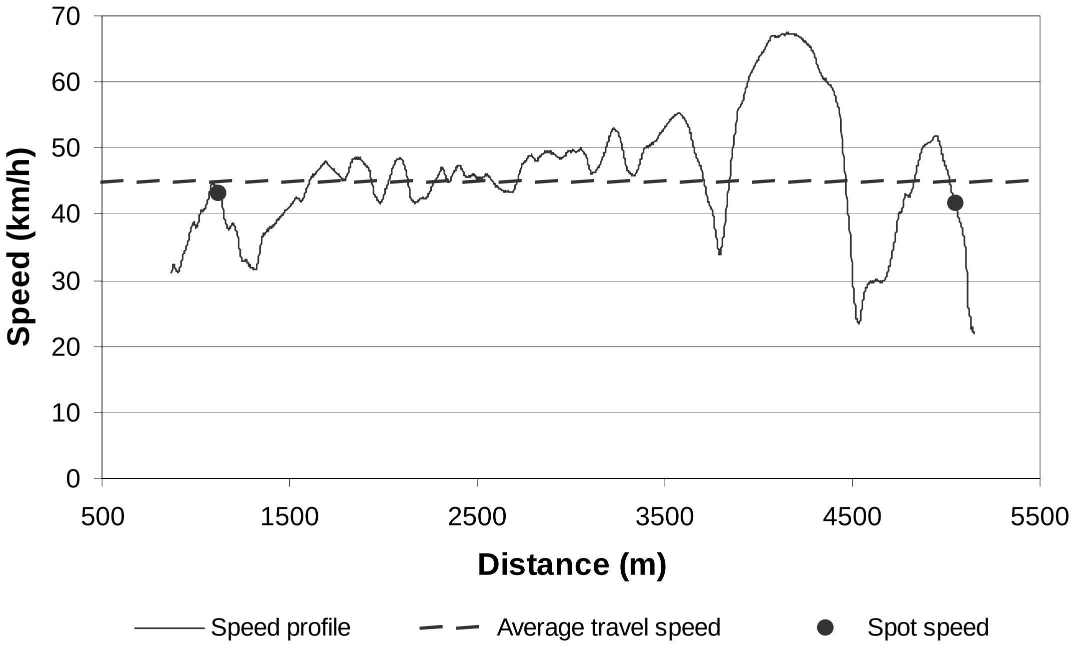


Figure 3:2 Example of mobile and stationary speed measurement, Harads Road southbound at 17.00 hours (Aronsson and Bang 2005).

The research strategy for the micro-study is illustrated in Figure 3:3. The first phase of the micro study was focused on gaining in-depth knowledge of factors that influence the individual driver's choice of speed for a variety of street types, urban environments and degree of exposure to side friction. The data used for development of speed models consisted of empirical behavioural data observed in the field and data from driving simulator experiments.

The empirical data was used to calibrate a microscopic simulation model which was applied for reproduction of driving patterns for a range of traffic flow and event scenarios. The traffic output from the microscopic model was then used to develop speed profiles and speed-flow relationships for urban streets.

A brief description of the model development process of the micro study is given below.

I. Identification of factors that affect driving pattern and speed choice.

II. Data collection of driver behaviour and speed profiles during field measurements using floating car technique.

III. Programming and calibration for a driving simulator for selected street environments.

IV. Data collection of speed profiles using the driving simulator.

V. Selection and adaptation of microscopic models for simulation of the traffic process in a street environment.

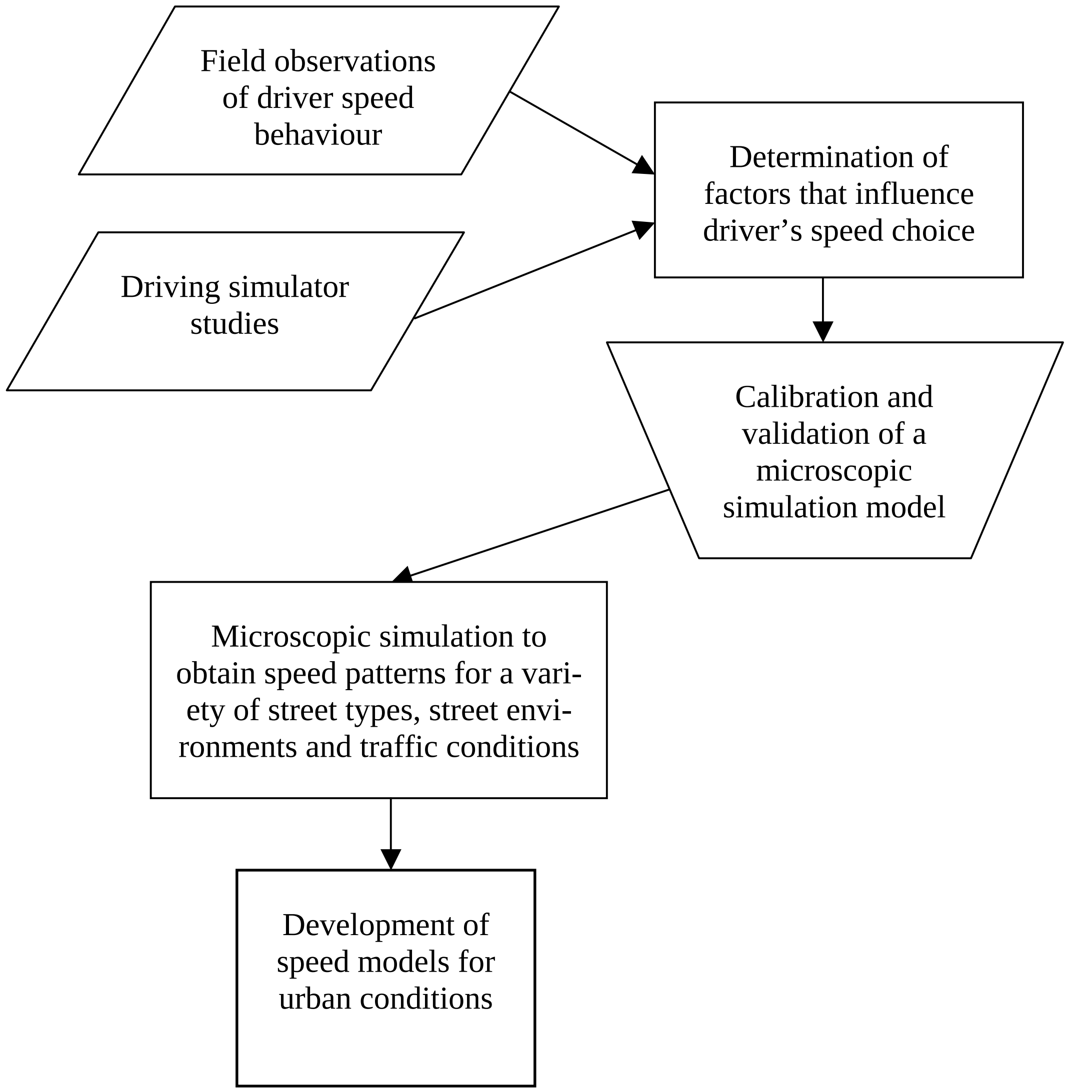


Figure 3:3 Overview of selected research methodology for the micro study.

VI. Calibration and validation of the microscopic simulation model, supported by driver behaviour data which were based on field and driving simulator studies.

VII. Simulations as a basis for development of general relationships between street design, street environment, traffic conditions, and speed.

The model development process for the macro study is illustrated in Figure 3:4. The flow and speed data was collected for five-minute periods of observation, and the average of speed and flow was calculated for predefined flow classes for each street type. The site characteristics for each studied site were entered into the databases, and multiple regression analysis was performed with speed as the dependent variable. The outcome from this process was speed equations for the investigated street types.

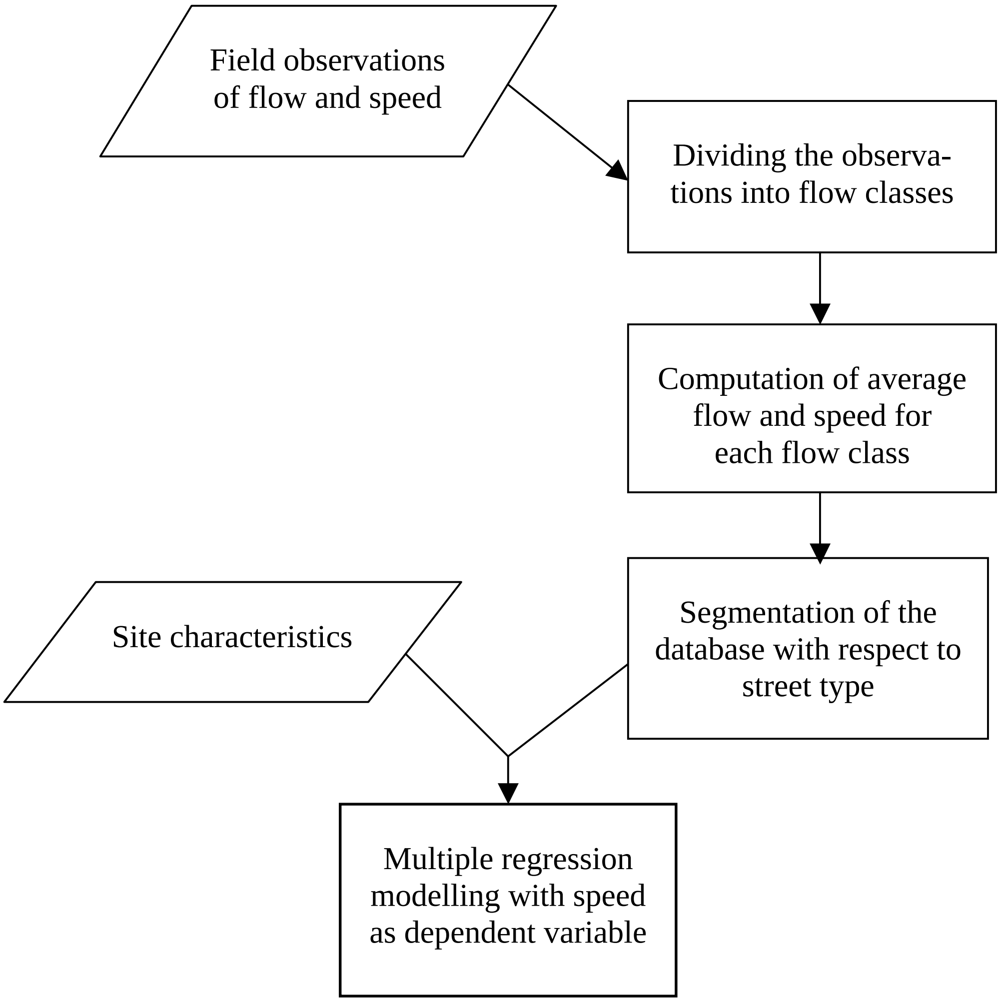


Figure 3:4 Overview of selected research methodology for the macro study.

3.2 THE NEED FOR DATA

3.2.1 Factors influencing speed

A variety of factors influence the desired speed of drivers along a street. When modelling speed on rural roads such factors are normally limited to traffic flow, roadway, cross-section and roadside variables as shown in the literature review in chapter 2. The Swedish Impact Assessment Catalogue (Swedish Road Administration 2001a) presents speed-flow relationships in such contexts for three street function types, combined with the number of lanes, and street environment types. A review of geometric design research in the U.S. (Fitzpatrick and Wooldridge 2001) identifies a demand for a revised design manual, which should include design consistency concepts and strengthened guidelines for consideration of pedestrian and bicycle movements. Previous studies referred to in the literature review (Aronsson and Bang 2005; Bang et al. 1995) have identified relationships between speed, street design and interaction with pedestrians and cyclists, buses stopping at stops, vehicles parking in or leaving kerbside parking places, but they have not been included in the design guidelines.

In this study additional data was needed due to the chosen “bottom-up” approach based on individual driver speed behaviour. Speed data for separate side-friction events were needed at a micro level as well as speed data at an aggregated level. The collected data should;

a) support direct empirically based model development;
b) be used as a basis for the development of synthetic street environments for use in simulator experiments; and
c) as basis for the calibration and validation of the microscopic simulation model.

The following types of data were needed:

- Driving patterns on main streets in urban environment, especially on streets with a low level of separation (i.e. with predominantly mixed traffic).
- Driver behaviour and interaction with pedestrians and cyclists, and other side-friction events.
- Traffic conditions, area type and land use.
- The design and function of the street, traffic control, devices etc.

This is in line with the Swedish Planning Guidelines (Johansson et al. 2004) and the Road and Street Design Handbook (Swedish Road Administration 2004), which present the concept of street environment description and the necessity to incorporate this in the design process. The planning guidelines define the street environment in terms of Character, Traffic network, Speed and Special qualities. The street environment is complex, containing several interacting variables that influence drivers’ speed choice, their travelling time, and the system’s accessibility to all categories of road user. Drivers’ speed choice is also influenced by interactions with other types of traffic. Examples of types of traffic and events that influence motorists’ speed choice are interaction with

- other motorists in the same lane or adjacent lanes,
- on-coming traffic intruding into one’s own lane,
- public transport stopping or leaving a stop,
- public transport making a special manoeuvre to turn at an intersection or leave a reserved lane,
- cyclists and moped riders in the same carriageway travelling in the same direction of travel,
- pedestrians and cyclists crossing the street, and
- stopping or parked vehicles in the lane closest to the kerb.

3.3 FIELD DATA COLLECTION

3.3.1 Site selection

The research focused on main streets divided into three types of facilities: arterials, suburban streets and urban streets. The arterials have medians and pedestrian and bicycle facilities physically separated from motorized traffic. The street segments were unsignalised, comprise motorised and non-motorised traffic, and include minor intersections where traffic on the studied streets has the right of way. A minor intersection is defined as an intersection with fewer than one thousand in-coming motor vehicles per day on each secondary approach to the intersection. The general geometric design criteria used for selection of sites and routes for the field study are presented in Table 3:1. Examples of each street type are given in the illustrations in Figures 3:5 to 3:7.

Table 3:1 Street design selection criteria of the field study

Street type A*: **Arterial***
- Function: Thoroughfare or approach
- Area: Semi-central area/suburb
- Cross-section: 4-lane, 2-way divided and undivided (total width approx. 20 m), 2 cases
- Public transport: In mixed traffic or dedicated lane, kerb-side stops
- Cyclists on link: Dedicated lane/separate cycleway alongside carriageway
- Cyclists in intersection: Separated or in mixed traffic (as defined by Brandberg et al. (1999) in Calm Streets!)
- Minor intersections: Stop or give way sign control on minor road entries
- No stopping/parking permitted along the carriageway

Street type B: ***Suburban street***
- Function: Other link in the main network (as defined in Calm Streets!). In some cases thoroughfare or approach.
- Area: Semi-central area/suburb
- Cross-section: 2-lane. May have central reservation with barrier to regulate speeds at intersections and passages
- Public transport: In mixed traffic or dedicated lane, kerb-side stops
- Cyclists on link: In mixed traffic or dedicated lane/separate cycleway alongside carriageway
- Cyclists in intersections: Separated or in mixed traffic
- Minor intersections: Stop or give way sign control on minor road entries
- Intersections/passages with or without speed regulation of 30 km/h
- Parking prohibition: Stopping permitted along the carriageway

Street type C: ***Urban street***
- Function: Other link in the main network
- Area: Central area
- Cross-section: 2-lane. May have central reservation with barrier to regulate speeds at intersections and passages
- Public transport: In mixed traffic or dedicated lane, kerb-side stops
- Cyclists on link: Separated or in mixed traffic
- Cyclists in intersections: In mixed traffic
- Minor intersections: Stop or give way sign control on minor road entries
- Intersections/passages with or without speed regulation of 30 km/h
- Parking prohibition: Stopping permitted along the carriageway

Figure 3:5 Example of an arterial.

Figure 3:6 Example of a suburban street.

Figure 3:7 Example of an urban street.

A large number of arterials, suburban streets and urban streets were screened in the selection process for the field study. Cross section, traffic flow, street function, and municipal traffic network studies were considered when determining the candidate streets. Most factors were studied and confirmed on-site. Streets where pedestrian and cycle activity was close to non-existent were excluded. Suitable sites were marked on maps. A representation of a variety of street types and geographical locations were crucial for the final site selection. Sites within 25 km travelling distance from the Royal Institute of Technology were given priority to in the selection. Lastly, planned road works and events were checked.

Based on the street design and geographical variation criteria stated above, field sites for the *micro and macro study* were selected in three cities: Stockholm (population: 1.8 million), Linköping (0.15 million) and Nyköping (0.05 million). The study involved nine routes on which the field data was collected by use of an instrumented vehicle for the mobile studies, short-base stations at the beginning and end of the route, and on-site inventory. Data for the long-base studies, that is travelling times on the route and amount of through traffic, were calculated from segments with two or more consecutive short-base stations. The technique of area wide video data collection was utilized for the collection of traffic data at the Nytorgs Street site in Stockholm. Apart from this site, the length of the selected routes measured from one to five km.

The selected routes are listed in Table 3:2 which includes details regarding street type, cross-section and route length. The selection of segment length for each street data collection was settled individually for each route based on design and traffic factors as well as consideration for realization of the field survey. For example the journey time for a round trip should be greater than 5 minutes in order to maintain the test driver's focus on the average car driving technique during the driving shift. Placement of the measurement stations was also crucial and each route in the field study contained two short-base stations or more. The stations were placed at locations identified as the boundaries where through traffic entered and exited the study area.

The posted speed limit was 50 km/h on most streets with the exception of the major part of the arterial Orby Boulevard where the posted speed limit was 70 km/h, and a speed limit of 30 km/h at a few school areas on Angstuge Road and Harads Road.

The data was collected between June and September 2002 and in May 2003, during daylight hours and under dry weather conditions. Eight hours of data were collected at each field site: four hours of morning traffic between the hours of 06.30 and 10.30, and four hours of afternoon traffic between the hours of 14.30 and 18.30. At the Stockholm sites, two hours of midday traffic were also collected. Both directions of travel were investigated. The data was mainly collected on Tuesdays, Wednesdays and Thursdays.

Table 3:2 The data collection sites in the field study.

City	Streets included in the route	Street type	Cross-section	Average daily traffic	Route length
Stockholm	Orby Boulevard	Arterial (70 km/h)	4 lane 2-way divided	30,000	4.4 km
	Kvarnbacks Road	Suburban street	2 lane 2-way undivided plus one transit lane	21,000	1.0 km
	Harads Road and old Sodertalje Road	Suburban street	2 lane 2-way undivided	12,000	5.2 km
	Nytorgs Street	Urban street	2 lane 2-way undivided	5,000	0.3 km
Linkoping	Malmslatts Road from Valla Rotary to Lasarett Street	Arterial	4 lanes 2-way divided, two of the lanes are transit lanes	17,000	1.4 km
	Old Tannefors Road	Suburban street	2 lane 2-way undivided	15,000	2.6 km
	Saint Lars Street	Urban street	2 lane 2-way undivided	14,000	1.0 km
Nykoping	Lennings Road	Suburban street	2 lane 2-way undivided	9,000	3.2 km
	Angstuge Road	Suburban street	2 lane 2-way undivided	7,000	1.1 km
	Brunns Street, Rep-slagare Street and East Rund Street	Urban street	2 lane 2-way undivided	12,000	2.5 km

An additional thirty-one sites in four cities from the SRA national short-base speed and flow surveys were brought into the *macro study*. The SRA chose a random sample of urban measurement locations and dates for their national surveys (Nilsson 2001). State and local authority roads in urban areas were included in the sample. The criteria for selection of which sites bring into the present study were as follows:

- A full representation of street types under investigation in the presented study.
- Find sites with various ranges of traffic flow, specifically the high flow range.
- The short-base site was located on the link where vehicles are not likely to accelerate or retard on the link.
- Feasibility to perform a post-inventory of street design, traffic regulation etc. of the station, accurate to day of actual measurement.
- The selected cities should if possible coincide with cities investigated within the traffic safety studies performed within the EMV project.

The SRA sites selected for the macro study are listed in table 3:3. The selected cities were Uppsala (population 0.2 million), Linkoping, Norrkoping (0.1 million) and Vasteras (0.1 million).The SRA short-base stations collected traffic data between the hours of 06.00 and 18.00 on one weekday per site. Data was collected in 2002 and 2003.

At most of the sites, the data was registered for one direction of travel. The posted speed limit was 50 km/h on most streets with the exception of a few arterials where the posted speed limit was 70 km/h.

A summary of the total number of sites investigated in the present study is shown in table 3:4.

Table 3:3 The SRA short-base sites which were selected for inclusion in the present study.

City	*Site name*	*Street type*
Norrkoping	Ståthöga Street, point T2873	Arterial (70 km/h)
	Lindö Street, point 2891	Arterial
	Malm Street, point 2874	Suburban street
	De Geer Street, point 2897	Suburban street
	Repslagare Street, point 2871	Urban street
	Bred Street, point 3227	Urban street
Linkoping	Glyttinge Street, point 2847	Suburban street
	Glyttinge Street, point 2863	Suburban street
	Skonberga Street, point 3331	Suburban street
	Djurgård Street, point 2886	Urban street
	Kasern Street, point 2857	Urban street
	St Lars Street, point 2867	Urban street
Vasteras	Johannisbergs Street, point T2320	Arterial (70 km/h)
	Norrleden, point T2350	Arterial (70 km/h)
	Stora Gatan, point 2338	Arterial
	Stora Gatan, point 2340	Arterial
	Köping Street, point 2342	Arterial
	East Ring Road, point 2352	Arterial
	West Ring Road, point 2339	Arterial
	Skultuna Street, point 2349	Suburban street
	Djuphamn Street, point 2343	Suburban street
	Anemon Street, point 2354	Suburban street
Uppsala	Råby Street, point 3262	Arterial
	Strandbod Street, point 2328	Arterial
	Fyrislund Street, point 3336	Arterial
	Fyrislund Street, point 3337	Arterial
	Fyrisvall Street, point 3264	Suburban street
	Rose Street, point 2361	Suburban street
	Bjork Street, point 2324	Suburban street
	Väderkvarn Street, point 2327	Urban street
	Vattholma Road, point 2359	Urban street

Table 3:4 The total number of the short-base sites selected for the present study.

City	*Arterial 70 km/h*	*Arterial 50 km/h*	*Suburban street*	*Urban street*	*Total*
Linkoping	2	2	3	4	11
Norrkoping	-	1	2	2	5
Uppsala	-	4	3	2	9
Vasteras	1	5	3	-	9
Stockholm	1	-	2	-	3
Nykoping	-	-	1	2	3
Total	4	12	14	10	40

3.3.2 Methods selection

A variety of techniques were employed for the collection of speed, traffic and street design data. At nine of the studied stretches, the field data was collected in three steps:

- ***Stationary survey.*** Traffic measurement stations, placed at the beginning and end of the route, for registering vehicles' passage times, vehicle type and spot speed and identity. The stations are also called short-base stations. Data from two or more consecutive short-base stations are input to a long-base study.
- ***Mobile survey***. A specially equipped car travels with the traffic and collects data along the route.
- ***On-site inventory*** of street design, street environment, street function, traffic control and devices, pedestrian and cyclist movement, traffic movement on side streets etc.

The employed data collection techniques are illustrated in Figure 3:8 and described in the next sections. At the Nytorgs Street field site, the technique of area-wide data collection was put into practice. The field site data was collected on consecutive stretches of streets with minor intersections. A minor intersection was defined as an intersection with fewer than 1,000 incoming motor vehicles per day on each secondary approach to the intersection.

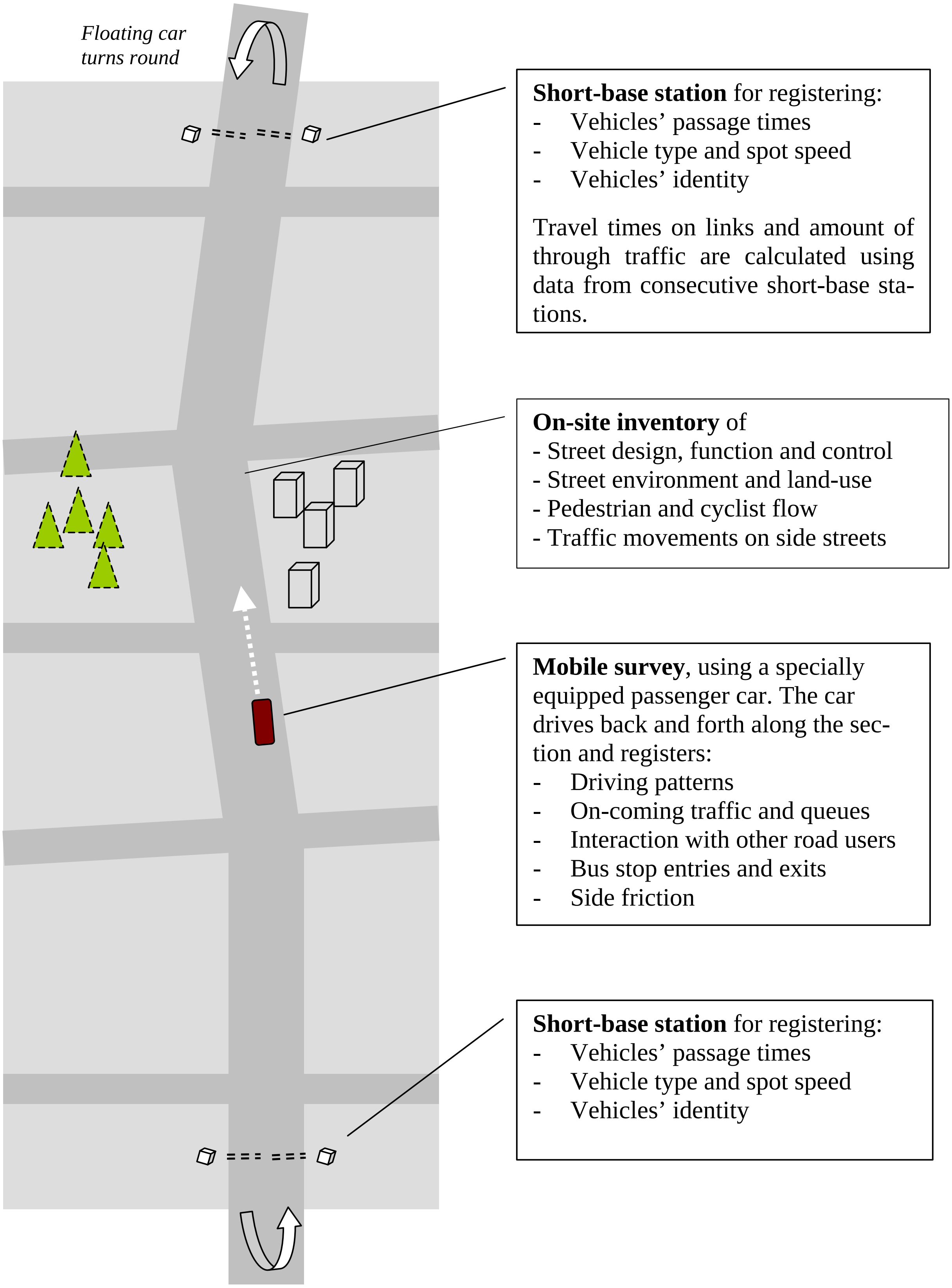


Figure 3:8 Data collection at the field sites.

Stationary data collection

Traffic flow, directional distribution and rate of through traffic was collected in short-base stations located at the entry and exit sections of each studied street segment, equipped with double pneumatic tubes plus video camcorders (Figure 3:9). This data was processed to obtain traffic flow, speed, and time headway distribution. Also, vehicle identity was obtained through number plate registration from manual collection backed up with video recording. Vehicles with an odd last digit in the number plate were registered in the field. Observers and cameras were placed out of sight of passing cars. Matching of vehicle identity and passage time data from the entry and exit short-base stations produced results for the long-base study in the form of average travel speed and ratio of through traffic. For the purposes of the male and female driver behaviour study, driver gender information was extracted from reviewing the video films.

Figure 3:9 Example of video recording from a short-base station.

Mobile data collection

In the mobile data collection, a specially equipped passenger car travelled on nine urban roads logging speed, time, distance travelled, distance to vehicle ahead, as well as recording on video camera of side-friction events. The car used for the mobile surveys, also referred to as the test vehicle, had the following data collection capability:

i) Automatic logging of time and distance travelled at frequent intervals (0.2 sec).

ii) Push-button set connected to the logging equipment for recording passage time at segment entry and exit, special events etc.

iii) Video camcorders mounted inside the vehicle with forward and backward views. Storage of the video recording in a digital VCR synchronized with the logging equipment. The video recording was used to gather information regarding time of occurrence of the following events:

- Encounters with vehicles in the opposite direction of travel
- Passage of occupied bus stop and parked vehicles
- Presence of waiting vehicles on cross street approaches
- Presence of pedestrians on the pavement
- Pedestrian presence at crosswalks (waiting to cross; crossing)

The test vehicle was operated with five drivers who were instructed to drive at the average speed of the traffic (implying they should overtake as many vehicles as they were overtaken by). The selected drivers were: female age 23, male age 26, male age 28, female age 38 and male age 56. These drivers were assigned to drive in one-hour slots scheduled at random. It would have been advantageous to include far more test drivers in the study to decrease the risk of bias, but this was not possible due to budget limitations. The results of the floating-car study were checked against travel time data obtained from the parallel long-base study for all the vehicles driving along the full length of each of the streets studied.

Area wide video data collection

In order to obtain full coverage of traffic conditions, side-friction events and resulting driving behaviour for a street segment, data was also collected using video recordings from a video tower. This was 15 metres high and had two remote controlled digital video cameras. This tower could cover a street segment of around 300 metres.

Semi-automatic video analysis (SAVA) was used to track the movements of all motor vehicles, pedestrians and cyclists with the purpose of obtaining driver behaviour data for speed profile and speed impacts of side-friction events. The video analysis software was developed at the department (Archer 2005). It is semi-automatic and enables recording of special events with a temporal precision of 40 milliseconds. The time-stamped passages and positional co-ordinates, or virtual street line markings, of the road users are registered manually from the screen. The traffic events of interest were recorded into a special output file covering vehicle identity and type, X and Y co-ordinates, virtual line number and the time of the event in milliseconds. The X and Y screen co-ordinates were mapped to real world X and Y co-ordinates in the software using orthagonalisation functions, as described by Archer (2005). The distances between any two points on the two-dimensional screen image can be measured in correspondence with real world three-dimensional distances once the calibration has been made.

The screen layout used for collecting vehicle and side-friction event data using the semi-automatic video analysis software is shown in Figure 3:10. The process of tracking a vehicle and its interaction with a pedestrian is illustrated in Figure 3:11. The second-by-second tracking began 8 seconds before the vehicle approached the crosswalk and ended 12 seconds later. The time and position of the pedestrian was tracked for three time notifications; before, while and after crossing the street.

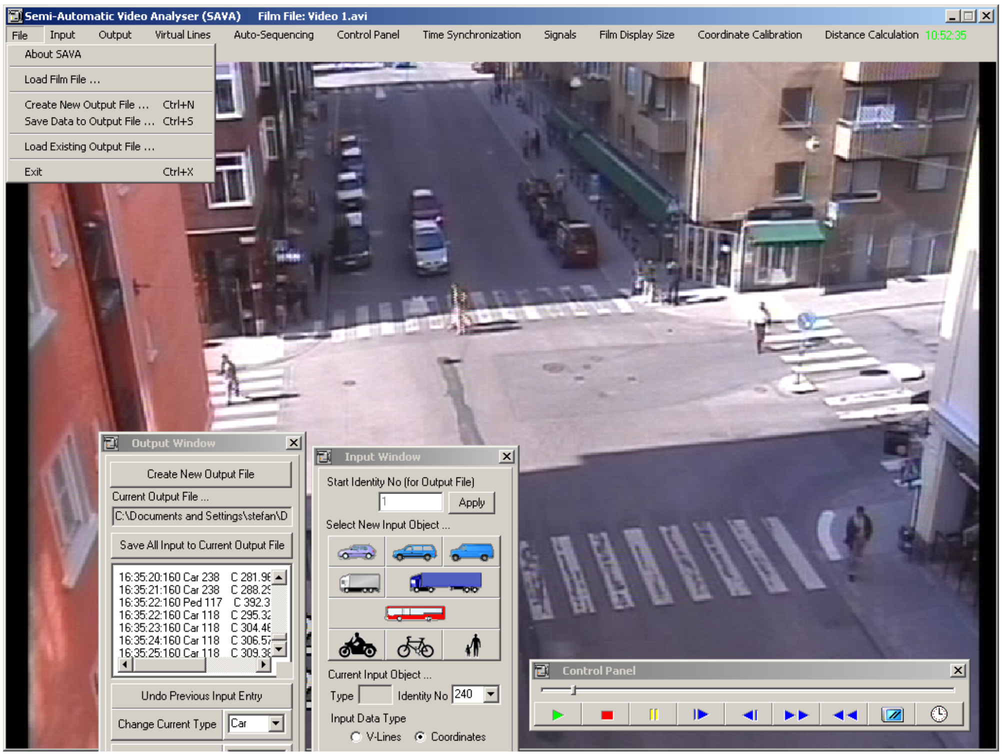


Figure 3:10 Vehicle and pedestrian interaction processed in the semi-automatic video analyser program. View of Nytorgs Street; vehicles driving southbound (facing the video tower) are investigated when interacting with other road users.

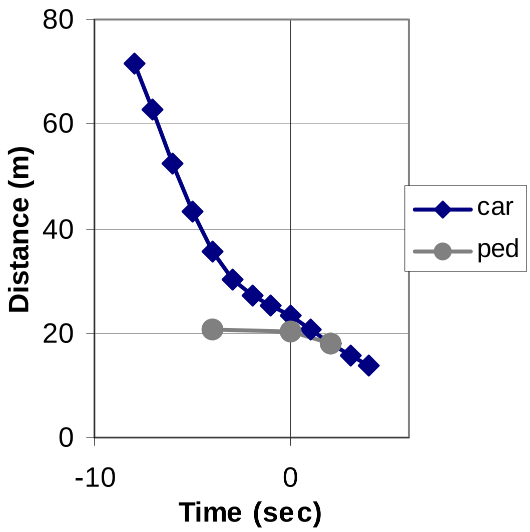


Figure 3:11 Example of the tracked distance down road, second-by-second, of the vehicle and pedestrian movement illustrated in the picture above.

The selection of vehicle movement and events for recording included the following steps.

I. Free-flow vehicles (unconstrained by other vehicles travelling in same direction) involved in different and independent events were located on the tape and investigated. Vehicle entry and exit points on the main street were registered, as was the movement of vehicles on side streets.

II. Tracking of a vehicles eight seconds prior to an event, following the vehicle second by second until four seconds after it had passed an interaction point. The tracking started over 45 metres before the interaction point, based on observations and work by Várhelyi (1996) in which a time to vehicle standstill of 2 to 4 seconds is set for the event a pedestrian approaches a crosswalk from the right. This implies a stopping distance of 22 to 44 metres for vehicles travelling with a speed of 40 km/h.

A number of vehicle speed profiles were plotted from the recordings of vehicle movements. The following types of events and their influence on the studied vehicle were examined:

a) oncoming vehicle,
b) bus exiting, entering or standing at bus stop,
c) vehicle exiting from side streets or waiting to exit,
d) pedestrian crossing the street or approaching a cross walk.

The events such as passing a cyclist in the same or opposite direction of travel, vehicle stopped or stopping at kerb, vehicle parked or about to park at kerb, and interaction with emergency vehicles were also studied, but to a less degree due to their lower frequency of occurrence.

Traffic and pedestrian flow, number of through vehicles and travel time passing the street link were also collected.

3.4 DRIVING SIMULATOR STUDIES

3.4.1 Background

Driving simulator studies were performed to augment the field data. In laboratory conditions, drivers encountered numerous sets of events when driving on a street modelled after one of the actual streets surveyed in the mobile study (Figure 3:12). The purpose of the driving simulator experiment was to supplement the field data collection of driving patterns. This was achieved through

a) inclusion of a large number of drivers representing gender and age groups,
b) experiments where the subjects drove in several scenarios with varying amounts of oncoming traffic and frequency of side-friction events,
c) validation against speed and travel time data collected in the field study.

A number of simulators were investigated and the finale choice was the interactive simulator system STISIM Drive developed by Systems Technology Inc. in California[3] (Allen, Rosenthal, Aponso et al. 2000). The driving simulator reproduces car driving in an urban street environment and contains interaction with other road users. The experiments were conducted in a laboratory with a mock-up car and wall projection of the simulated street. The vehicle had a fixed base and was connected to a computer and equipped with steering wheel, pedals, automatic gearbox, and feedback mechanisms for

[3] www.systemstech.com

steering wheel movement. A high quality sound system reproduced engine noise and vibrations, tire screeching and crash sounds. The street environment in the driving simulator was reproduced from technical drawings of the street and videotapes collected during previous steps in the data collection.

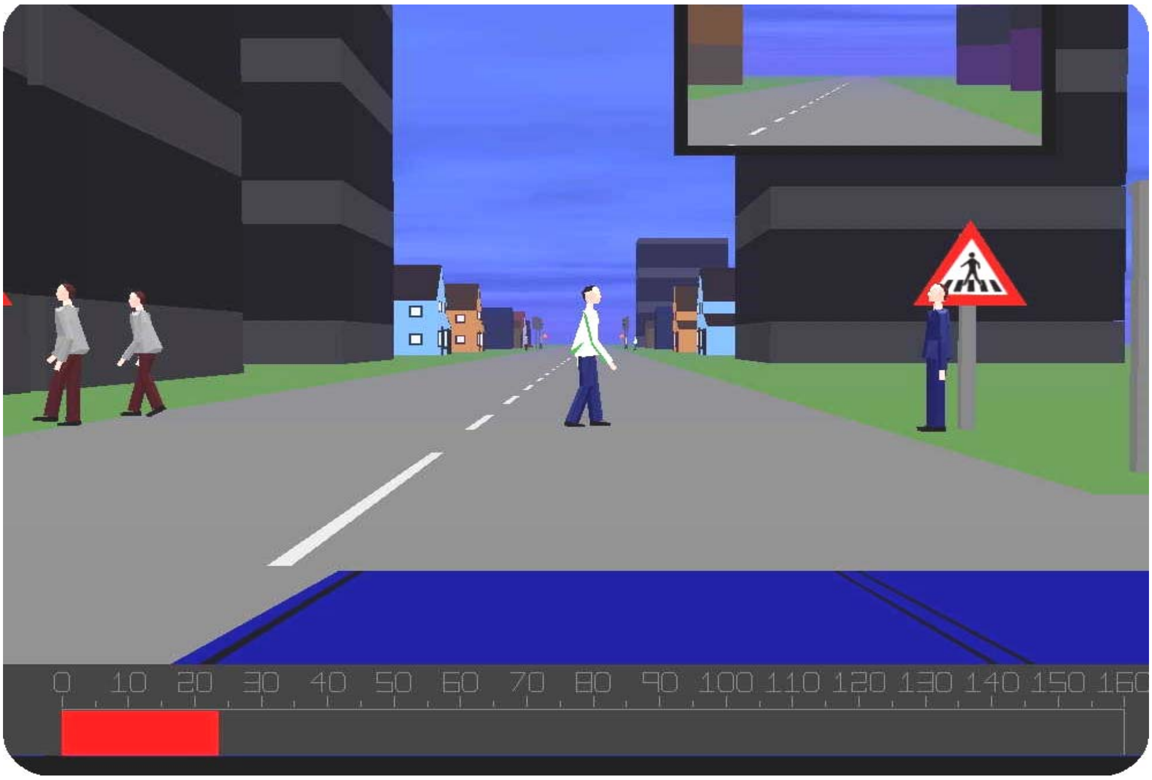


Figure 3:12   Example of animation of driving in a simulator.

3.4.2 Site selection

One of the routes surveyed in the field was selected for the street design of the driving simulator experiments. The following main requirements were essential for the selection of a test site to be used.

- Ability to reproduce the test site from drawings and videotapes collected during previous steps in the data collection.
- Ability to validate the simulator studies to real-life field study data.
- Traffic flow and the frequency of events on the street in the upper range.

The selected street modelled in the driving simulator was the St. Lars Street of the field study (Figure 3:7). It was an urban street with a different mix of all traffic events; oncoming traffic, pedestrians walking on the pavements and crossing the street at crosswalks, vehicles waiting on side street and buses stopping at bus stops.

3.4.3 Calibration and validation

The output of the validation scenario of the driving simulator was tested and validated against speed profiles and travel times collected in the field. The validation scenario was designed after the test vehicle run number 9 on Saint Lars Street, at the end of the morning peak hour, performed by driver number 3 (Figure 3:13). Driver 3 was a man, 58 years of age. Side-friction events which occurred in the run are marked on the x-axis of the figure.

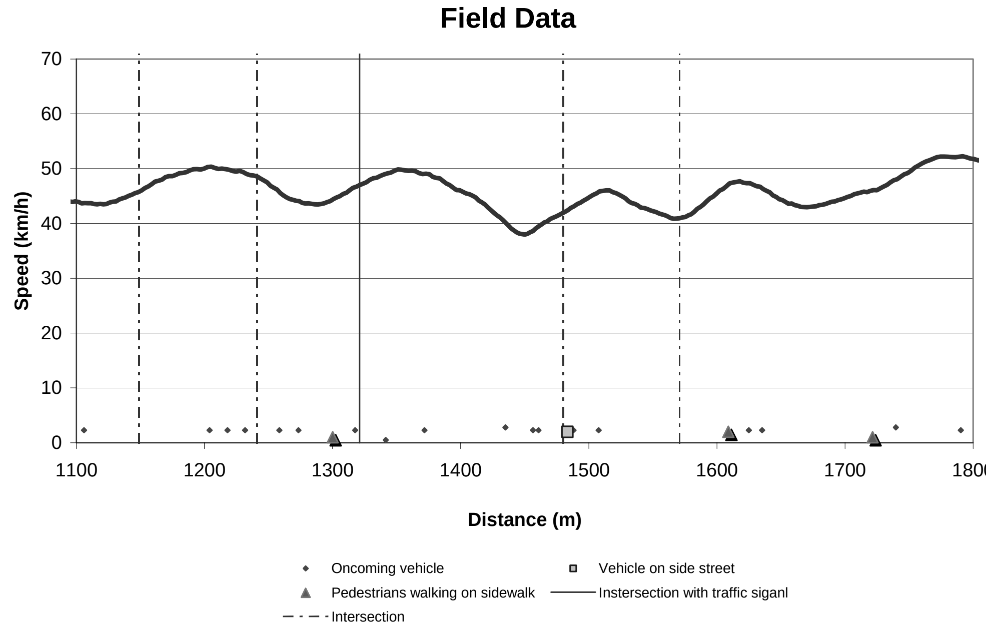


Figure 3:13 Illustration of the impact on a speed profile of different side-friction events. From field study, St Lars Street southbound, run no 9 by driver number 3.

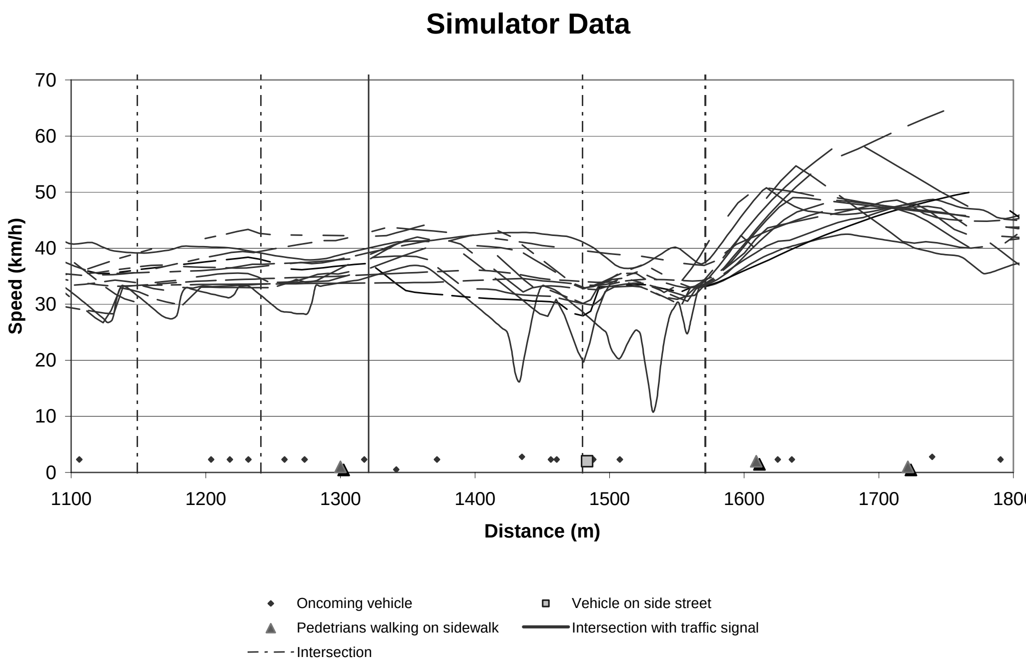


Figure 3:14 Speed profiles of the simulator study, validation scenario driven by driver number 3.

Driver number 3 drove more conservatively in the simulator than in run number 9 in the field study for the distance illustrated in Figure 3:14 (metres 1,100 to 1,800). The harmonic mean speeds measured per 20 metres travelled way in the simulator study were on average 38.0 km/h, standard deviation 5.0. The average speed measured in run number 9 in the field study was 42.5 km/h with a standard deviation of 3.1. The travel speeds of the validation case were not within one standard deviation of the observed value which is a validation criteria practiced for simulation tools (Choa, Milam, and Stanek 2003). However, comparisons of speed behaviour for side-friction events and travel time data proved that output of the simulator generally agreed with the observed data. The speed reductions made by driver number 3 in the validation scenario for side-friction events (in this case intersections and waiting vehicle on a side street) were compared with field data. The graphs in Figure 3:13 and 3:14 showed that the speed reductions made in the field and simulator generally did not differ. The average travel times of driver number 3 in the driving simulator showed good agreement with the peak hour field data of the test vehicle in uninterrupted flow. This is discussed below.

The comparison of travel times measured in the field and in the driving simulator are shown in Table 3:5. The distance between the two travel time measurement points was 565 metres (between meters 1,121 to 1,686). The average travel time of driver number 3 in the driving simulator validation scenario was 16 % greater than the field data of run number 9 and 3 % greater than peak hour field data. Moreover, the average travel time of all subjects in the driving simulator (48.2 $\pm$ 1.0 sec) did not differ significantly from the field data of driver 3 in run number 9.

Table 3:5 Comparison of travel times measured in the field and the driving simulator.

	Measure	Travel time (sec) Southbound
Driving simulator	Average travel time of driver number 3 in the validations scenario	55.8 $\pm$ 0.9 SD 2.9
	Average travel time of *all subjects* in the validations scenario	48.2 $\pm$ 1.0 SD 6.4
Field	Travel time of the test vehicle in run number 9, driven by driver number 3	48
	Average travel time during peak hour of the test vehicle in uninterrupted flow, driven by driver number 3	54.0 $\pm$ 3.0 SD 5.3

Furthermore, graphs of the observed and simulated speed behaviour for the event of a pedestrian approaching a crosswalk (presented in Chapter 4) were compared for validation purposes. The data collected in the driving simulator showed good agreement with the observed data.

3.4.4 Conduction of the experiments

The experiment consisted of a practice run, experimental runs with urban street scenarios and a questionnaire on driving habits, traffic accidents and computer game habits. The participants were encouraged to drive as they would normally. Each subject encountered the same fixed sequence of scenarios including routes with a varying frequency of oncoming traffic, traffic on cross streets, pedestrians and buses at bus stops (Table 3:6). The subjects were unrestrained by any vehicle in the same direction of travel.

The subjects were recruited from the university faculty, staff and students not otherwise engaged in the project. Participation was rewarded with a cinema voucher. Forty-three subjects participated in the study conducted in October 2004. Three of the subjects experienced simulator sickness and could not complete the experiment. Two subjects were not comfortable with the simulated driving task and completed the experiments after exceptionally long travel times. Additional subjects were therefore recruited for the experiments. The thirty-nine participants who did complete the experiments were, on average, 39 years old (range 21- 64 years of age) and had held a driving licence for a mean period of 19 years. The median category for mileage driven during the past year was 10,000 to 15,000 kilometres. Of the participants, 46 % were women and 54 % were men.

Table 3:6 The driving simulator scenarios.

No.	*Scenario description*	*Route length (m)*	*Duration (minutes)*
0	Practice run.	8,500	15
1	Introduction scenario; an urban street with oncoming traffic, pedestrians walking on the pavements, vehicles waiting on side streets. Traffic events similar to scenario 4.	1,900	5
2	Null scenario; an urban street with zero traffic events.	1,900	5
3	Base scenario; an urban street where all traffic events occurs; oncoming traffic, pedestrians walking on the pavements and crossing the street at crosswalks, vehicles waiting on side streets and buses stopping at bus stops.	1,900	5
4	Validation scenario; an urban street where traffic events occur similar to a floating car run no. 9 on Saint Lars Street; oncoming traffic, pedestrians walking on the pavements, and vehicles waiting on side streets.	1,900	5
5	A scenario with several traffic events except oncoming traffic.	1,900	5
6	A scenario with all types of traffic events including buses at bus stops and slightly reduced carriageway width.	1,900	5
	Total route length and average duration of the experiment.	20,000	45

3.4.5 Data reduction

The data reduction methodology for the general driving simulator study consisted of four steps.

1) Draw speed profiles along the studied routes for each driver and studied scenario based on speed, space and time data (Figure 3:15).

2) Calculate the average travel speed on chosen segments and sections of the street. Exclude extreme travel times.

3) Calculate and enter the number of events per 100 metres travelled way and other street and land-use factors into a database for regression analysis.

The steps were performed for all subjects and for male and female subjects respectively.

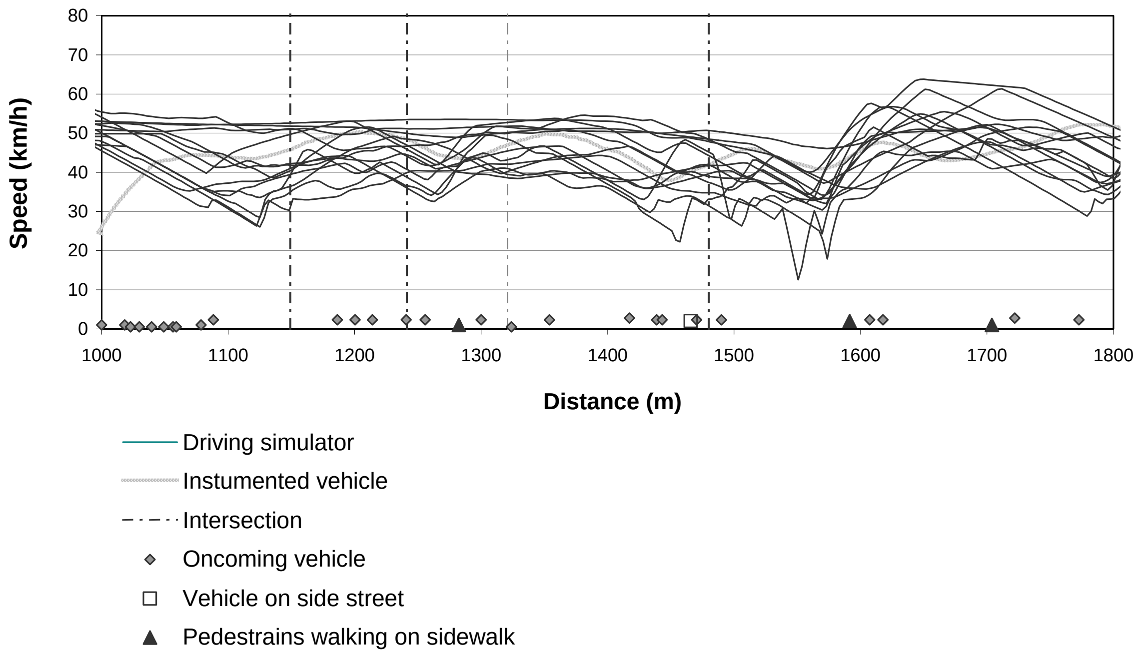


Figure 3:15 Speed profiles from the driving simulator study.

3.5 DATA REDUCTION AND ANALYSIS OF THE MICRO STUDY

3.5.1 Overview of the micro study

The principal requirement when selecting methods for data collection was the ability to capture the influence of side-friction variables on driver speed, and to quantify the impact. Two modes of investigation were developed and applied; the micro and macro study (Aronsson and Bang 2007). The research strategy of the micro study was to collect:

a) Data at the individual driver behaviour level for a range of street types, traffic flow and exposure to side-friction, and
b) Speed – flow relationships produced by micro simulation modelling

The selected methods for the first step were data collection in the field and through controlled experiments in a driving simulator. The collected data consisted of

- Speed profiles
- Traffic flow and conditions in the vicinity of the studied driver
- Street design and environment
- Pedestrian and bicycle movements

The second step in the micro study was to enhance a microscopic traffic simulation model with the collected behavioural data, run it for a range of traffic flow and pedestrian movements, and collect speed-flow relationships and average travel speed data. Details of the microscopic simulation can be found in chapter 5.

A number of authors in the reviewed literature collected speed profile data and modelled it with side friction, street design and land use: e.g. Fitzpatrick et al. (2000) and Wang et al. (2006). The authors employed *mobile collection techniques*, i.e. specially equipped vehicles, for the collection of individual speed profile data. The *video-analysis method* developed by Archer (2005) referred to in the literature can, if further elaborated, utilized for speed profile data collection. Another means of collection speed profile data are exemplified by the *driver simulator studies*, for example those performed by Hakamies-Blomqvist et al. (2001) and Klee et al. (1999). These three methods were considered to be most valuable for the process of gaining more knowledge of the speed impact of different conditions and side-friction events, specifically speed profile data collection. The methods developed and amplified for the purpose of the study were as previously described in section 3.3.

3.5.2 Data reduction

General

The purpose of the data reduction of the micro study was to

a) produce speed profile data for various side-friction events;
b) produce databases of average travel data, design and number of events per distance for multiple regression analysis of speed as the dependent variable;
c) collect information on vehicle and pedestrian movements to insert into the microscopic traffic simulation model;
d) provide traffic and driver behavioural input to the production runs of the micro simulation model and produce speed-flow relationship data.

Details of data reduction for the different data collection methods are listed below.

Mobile studies

The data reduction methodology for the mobile field study consisted of five steps.

1) Process the data from the traffic measurement stations to determine traffic flow, amount of heavy vehicles and the times of morning and evening peaks. Calculate travel times and percentage of through traffic for selected hours.

2) Screen the data collected by the specially equipped car, including speed, traffic conditions, and video recordings made using the car, and select time periods of in-

terest for the next step. For most sites, two hours of morning traffic data and two hours of afternoon data were of sufficient interest for more detailed study. Forty hours of data were thus selected for the next step.

3) Select and process the data to gather information about the speed of the specially equipped vehicle, the distance it travelled, whether it was a free or non-free vehicle, and the amount of interaction of various kinds with other road users while driving the route. Speed profiles of the driven routes were calculated and drawn.

4) The time periods from each site were narrowed down for further detailed analysis and study.

5) The time periods selected for the individual streets were analysed in detail. Information on interaction times with motorized and non-motorized traffic was entered into a spreadsheet together with time, speed and alignment data from the specially equipped car

Examples of collected speed profiles of the mobile runs are illustrated in Figure 3:16.

Figure 3:16   Speed profiles from mobile studies on St. Lars Street.

Area-wide video data

The material was reviewed for traffic events of interest and analysed by means of the SAVA computer program. The video recorded data was reviewed to gather overall information about travel time, distance travelled, x and y-coordinates of free vehicles interacting with oncoming traffic, vehicles exiting from side-streets, crossing pedestrians, in-street cycling and buses at bus stops. Two hours of afternoon traffic data were selected for more detailed data reduction of individual driver behaviour. Examples of speed profiles are given in Figure 3:17. Data on traffic flow, travel times and flow of pedestrians walking on the pavement for five minute observation periods was collected for one peak hour.

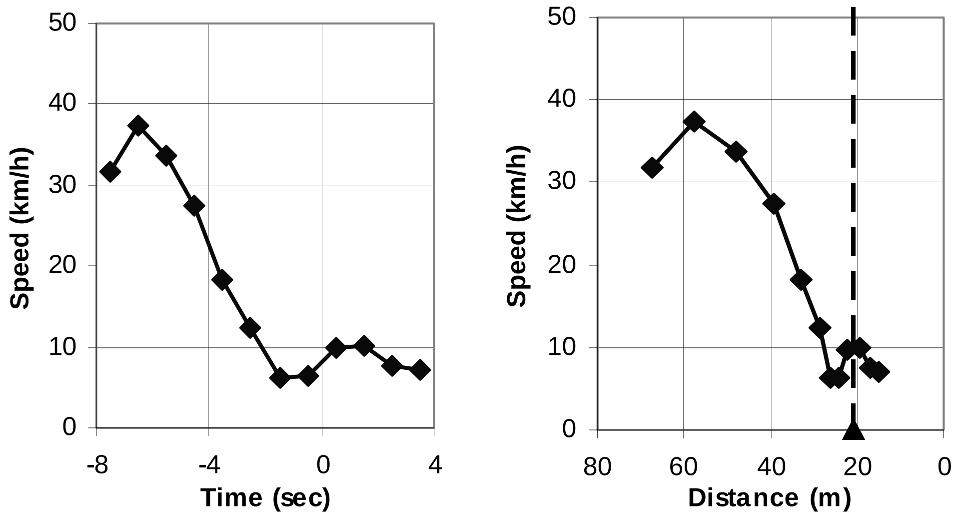


Figure 3:17 The vehicles speed profile, in time and space respectively. The front of the vehicle approaches the crosswalk at second 0. The crosswalk location is marked with a dashed line.

Driver gender studies

When selecting and reducing data for the study of female and male driver behaviour, the chief criterion was to find short-base sites in the micro field study where the video recordings enabled a clear and interpretable view of the driver. Light conditions and the technical quality of the films were decisive when selecting hours for extraction of gender information. For example, on several streets the morning sun illuminated the inside of vehicles which facilitated the possibility to identify driver gender. The representation of different street types and traffic conditions was also very important. A total of nine short-base sites out of eighteen field sites were chosen for the gender data collection (Table 3:7).

All vehicles passing the short-base stations during the selected time periods were examined. Driver gender information was extracted from reviewing the video films and entered in the traffic data file collected at the specific site, see table 3:8. The drivers were coded male, female or not visible. Clock times of camera and log were synchronized before gender information was entered into the log file. The view of the driver was in some cases not clear, especially inside trucks, making recognition of gender difficult. The vehicle type truck was therefore excluded from the driver gender study. The very different traffic performance of trucks, and the observed small ratio of women driving them, contributed to this decision. Vehicles passing the short-base station at extreme low or high speed were excluded. The extreme values were identified from box-plots of the site data. Observed values whose distance from the nearest quartile was greater than 1.5 times the inter-quartile range were defined as outliers and excluded.

The significance tests of equality of means of male and female driver behaviour were performed for cars and vans of which driver gender could be determined.

Table 3:7 The selected hours and sites for gendered analysis of the short-base sites. The analysed long-base sites are noted in the table.

City	Streets included in the route	Morning Peak	Off-peak	Afternoon Peak
Stockholm	**Orby Boulevard** eastbound site Sunday Street		8.30-9.30	
	Harads Road eastbound site Stuvsta Rotary		8.30-8.52 and 12.00-13.00	
Linkoping	**Malmslatts Road** eastbound site Valla Rotary site Griftesgarden		 8.30-10.30 8.30-10.30	
	Old Tannefors Road westbound site Pelagonen			15.45-16.00 and 16.15-17.15
	Saint Lars Street southbound site Linné Street site Folkungavallen	 7.30-8.30	 14.50-15.50 8.30-9.30	
Nykoping	**Lennings Road** westbound site Harbour	7.30-8.30	6.30-7.30 and 8.30-10.30	14.30-17.00
	Brunns Street Eastbound site Repslagare Street	7.30-8.30	6.30-7.30 and 8.30-10.30	

Table 3:8 Example of the log file from the short-base station Brunns Street shown in Figure 3:9. Gender 1 = male, 2= female or 3=driver not visible on film.

Passage time	Gender	Vehicle type	Speed (km/h)	Axle spacing (m)	Headway (sec)	Time to vehicle behind (sec)
07:32:37534	2	Car	34,9	2,3	7,9	23,2
07:33:00760	3	Car	26,0	3,5	23,2	2,6
07:33:03357	1	Car	23,9	2,5	2,6	2,6
07:33:05940	1	Car	30,3	2,4	2,6	2,5
07:33:08434	2	Car	29,6	2,4	2,5	1,3
07:33:09749	3	Car	30,2	2,6	1,3	50,3
07:34:00046	2	Car	36,6	2,2	50,3	8,8
07:34:08864	2	Car	36,9	2,3	8,8	16,4
07:34:48440	1	Car	29,9	2,5	17,0	1,6
07:34:50035	2	Car	30,6	2,4	1,6	2,6
07:34:52669	2	Car	31,0	2,2	2,6	1,8
07:34:54446	1	Car	36,3	2,4	1,8	15,4
07:35:09873	3	Car	35,3	2,4	15,4	18,4
07:35:28305	1	Car	33,4	2,4	18,4	18,3
07:35:46574	1	Car	30,6	3,0	18,3	10,2

3.5.3 Data analysis

Time-space data from the floating car observations and similar data obtained from tracking of individual vehicles from the video tower recordings were used to analyze the impact on driver speed pattern of different side-friction events. The speed profile data was combined with the side-friction event data in order to analyze the impact on speed for drivers experiencing different types of events. The speed impact of individual events was analyzed in detail using the following procedure:

1. Determination of vehicle speed before being exposed to the event (normally determined as speed at arrival a specified distance from the event location).
2. Tracking of vehicle speed changes while approaching, passing and leaving the event location.
3. Determination of maximum speed difference during this process.
4. Recording of vehicle behaviour (e.g. passing or stopping to let a crossing pedestrian pass).

The results from the studies of vehicle movements were used to determine typical speed pattern impacts of different types of events. Similar analysis was also conducted using the variable “distance to encounter”.

The driving simulator results were used to analyse the impact of different events in the same way as described above for the mobile studies. The drivers did not encounter vehicles driving ahead of them in the same direction of travel, and were thus considered to represent unrestrained vehicles. Male and female speed profiles produced in the driving simulator study were compared and analysed.

3.6 DATA REDUCTION AND ANALYSIS OF THE MACRO STUDY

3.6.1 Overview of the macro study

The macro study was based on flow and speed averages for selected links with short- and long-base data collection methods. The collected data consisted of

- Spot speed data
- Traffic flow
- Street design and environment
- Pedestrian and bicycle movements
- Travel time data

The methodology of the macro study was to analyze the variables listed above using multiple regression techniques with average speed as the dependent variable. A similar analysis method to that used by Bang, Carlsson and Palgunadi (1995), Bang et al. (1998) and Wang et al. (2006) was applied to capture the influence of side friction, street design and land use on speed. The collected data was thereafter supplemented with detailed descriptions of the traffic conditions that affected the speed observations (amount of side-friction etc), the traffic environment around the measurement location, and street variables (carriageway width, lanes, reserved lanes, traffic control and regulation features, traffic on intersecting streets, and the surrounding environment).

3.6.2 Data reduction

Short-base data

The field data from each short-base site was entered into a database including site characteristics and 5-minute observations of traffic flow and average speed (Table 3:9). The street site variables are explained in detail in the next chapter. The traffic data was then aggregated as follows:

1. Distributing the site observations in flow classes (e.g. 1-5 veh/5 min, 6-10 veh/5 min etc.).
2. Computing the mean flow and speed for each flow class for each site.
3. Segmentation based on street type (arterial, suburban street, urban street).

Table 3: 9 Example of extract from the short-base database.

Space mean speed (km/h)	Traffic flow per 5 min	Structure of environm.	Number of lanes	Lane width (m)	Median indicator	Distance to next inter-section (m)	Street function	Bicycle lane indicator	Bus stop indicator	Intersections per km	Parking indicator	Av. number of crossing pedestrians and cyclists per 15 min and 400 m
34.0	22.5	0	1	4.5	0	37	1	0	0	7	0	25
31.5	26.9	0	1	4.5	0	37	1	0	0	7	0	25
32.0	32.5	0	1	4.5	0	37	1	0	0	7	0	25
33.8	9.0	0	1	4.5	0	125	1	0	0	8	0	25
33.0	12.7	0	1	4.5	0	125	1	0	0	8	0	25
32.5	17.8	0	1	4.5	0	125	1	0	0	8	0	25
33.1	23.7	0	1	4.5	0	125	1	0	0	8	0	25
34.9	26.0	0	1	4.5	0	125	1	0	0	8	0	25
37.2	12.5	0	1	4.5	0	43	1	0	0	5	0	15
42.6	18.5	0	1	4.5	0	43	1	0	0	5	0	15
42.0	23.1	0	1	4.5	0	43	1	0	0	5	0	15
40.4	28.1	0	1	4.5	0	43	1	0	0	5	0	15

The pedestrian and cyclist movements measure were expressed as an average number of crossing pedestrians and cyclists collected for a time period of 15 minutes. The observed stretch was 200 metres upstream and downstream of the short-base station, for both sides of the road. The time period and distance were selected for practical realization of manual observations performed by one observer. The measure can be converted to individuals per hour and kilometre by multiplying by ten. Pedestrians and cyclists walking along the street were also included in the measure, but on a secondary level, and there were observed to be more of them than the average number of crossing pedestrians and cyclists. The following variable ranges were used from the short-base field observations.

Average number of crossing pedestrians and cyclists:

0 - 9 per 15 min and 400 m
10 - 19 per 15 min and 400 m
20 - 29 per 15 min and 400 m
30 - 40 per 15 min and 400 m

For the studied road segments, the entry and exit short-base survey station data of vehicle passage time and number plate was analyzed to obtain travel time data for the segment. Average travel time and speed data, including confidence intervals, and the ratio of through traffic were computed. For example, the average travel speeds ranged from 27 to 39 km/h on the studied urban street links. These results were used for validation of the driving simulator, the microscopic simulation model, and the macro models.

The speed profiles and average travel times, collected for the gender study, were stratified for male and female driver populations. Of importance when analyzing the speed data of individuals was to note if the driver was restrained by a vehicle in front of them or not. The speed choice of unrestrained drivers was considered to best represent speed choice made with regard to street design, environment and individual driving style preferences. Descriptive statistical analysis was applied on the data collected from the short-base stations. The data was tested for differences in driver behaviour between men and women.

Long-base travel time data

For each studied street route, the entry and exit short-base survey station data of vehicle passage time and number plate, for vehicles with an odd last digit, was analysed to obtain travel time data and percentage of through vehicles for the route. The data was collected for peak hours and off-peak hours as shown in table 3:10. The off-peak hours were mainly selected among the time periods of in-field collected number plates. Extreme travel times were decided based on frequency distribution for each studied route and time period and excluded from the data material.

The average travel time of the through vehicles on one long-base route (Table 3:11) was stratified for male and female driver populations. Descriptive statistical analysis was applied on the collected data and the data was tested for differences in driver behaviour between men and women.

3.6.3 Data analysis

The short-base site data was used for multiple regression analysis for each street type separately and all types combined with speed as the dependent variable.

The entry and exit short-base survey station vehicle passage time and number plate data was analysed to obtain average travel time and speed for the segment. Outliers were excluded and the average travel speed data was computed. A speed flow analysis was performed as a check of the gathered data. The influence of through traffic ratio on average speed at the peak hour was analysed for 16 of the short-base stations using box plots and multiple regression analysis.

Behaviour data was stratified for male and female driver populations for a range of traffic conditions. Descriptive statistical analysis was applied on the data collected at the short and long bas stations. The data was tested for differences in driver behaviour between men and women.

Table 3:10 Selected routes and hours for the travel time study.

City	Streets included in the route	Morning Peak	Selected off-peak period	Afternoon Peak
Stockholm	Kvarnbacks Road	07.30-08.30	09.00-10.00	
	Harads Road	07.30-08.30	12.00-13.00	
	Nytorgs Street		14.30-15.30	15.30-16.30
Linkoping	Malmslatts Road	07.30-08.30	08.30-09.30	16.30-17.30
	Old Tannefors Road		09.00-10.00	15.45-16.45
	Saint Lars Street	07.30-08.30	08.30-09.30	16.00 - 17.00
Nykoping	Lennings Road		07.00-07.30, 08.30-09.00	16.10 - 17.10
	Angstuge Road	07.30-08.30	08.30- 09.00	
	Brunns Street, Repslagare Street and East Rund Street	07.30-08.30	08.30-09.30	

Table 3:11 Selected site and time period of the travel time study of female and male drivers.

	Streets included in the route	Time period
	Old Tannefors Road in Linkoping , Westbound	16.15-16.45

4. RESULTS OF THE EMPIRICAL STUDIES

This chapter reports the data reduction and results of the field and driving simulator studies.

4.1 MICRO STUDY OF INDIVIDUAL DRIVER BEHAVIOUR AND SPEED PATTERNS

4.1.1 Reduced data material

The reduction of data collected in the mobile studies, area-wide video surveys and driving simulator studies resulted in a range of speed patterns for a number of side-friction events. Table 4:1 exhibits the total number of side-friction events detected in the micro study. The side-friction events occurred randomly in the field study and were rare at some of the mobile study sites. The collected number of events, e.g. passing an occupied bus stop, was zero at most sites. Exceptions were Kvarnbacks Road, where the instrumented vehicle passed a bus at a stop once, Harads Road eight times, and Saint Lars Street, six times. The frequency of events was greater at the site of the area-wide video survey. On the other hand, the side-friction events did not occur on a random basis in the driving simulator since the subjects encountered predefined sets of events when driving in the street scenarios. The driving simulator experiment provided speed patterns for thirty-nine subjects.

Table 4:1 The total number of side-friction events detected in the micro study.

	Number of side-friction events detected									
	Passing of a side street with waiting:		Pedes-trian at cross-walk	Passing an oc-cupied bus stop	Passing stopped or parked vehicle	Travelling in the studied direction and passing a:			Oncoming Traffic:	
	Vehi-cle	Cyclist				Cyclist in street	Pedestrian or cyclist on		Cyclist in street	Vehicle
Studied route							Pave-ment	Track		
Orby Boulevard	10	1	2	0	0	0	5	5	0	>50
Malmslatts Road	0	0	20	0	0	0	34	20	0	>50
Lennings Road	10	0	20	0	0	0	0	25	0	>50
Kvarnbacks Road	0	0	0	1	3	0	25	0	0	>50
Harads Road	10	3	1	8	2	1	40	0	1	>50
Old Tannefors R.	10	2	6	0	2	12	17	1	10	>50
Brunns Street	8	1	10	0	3	4	19	6	1	>50
Angstuge Road	8	0	4	0	0	0	0	35	1	>50
Saint Lars Street	68	5	16	6	0	26	300	0	22	>100
Nytorgs Street	24	1	50	0	0	5	100	0	5	48
Total of field sites	148	13	129	15	10	48	540	92	40	>500
Driving simulator (St. Lars Street)	40	0	40	40	0	0	300	0	0	>100

4.1.2 Identification of factors which influence average free flow speed

The purpose of the calculations presented in this section was to identify factors which influence speed. Data from the mobile study and driving simulator was used. Field data of Saint Lars Street (Figure 3:7) was segmented for ten sections in the southbound and northbound direction of travel. The number of pedestrians crossing the street or walking on the pavement ranged from 150 to 2,100 per hour and kilometre. Equation 4:1 shows results obtained using multiple regression analysis of the impact of different types of events during each run with the test vehicle. The independent variables were traffic flow per direction, lane width, pedestrian and cyclist movement and vehicles waiting on side streets. The variables were statistically significant on the 0.05 level. The R2 value of the analysis was 0.62. The variable Number of pedestrians crossing the street or walking on the side had a significant impact on speed, as did the flow per hour of vehicles in the opposite direction of travel. The constant of the regression analysis is greater than the field data average (Figure 3:16, Table 3:5), but is consistent with the actual range of independent variables (e.g. flow of vehicles in the opposite direction of travel was constantly over 200 vehicles).

Average free-flow speed, field study (4:1)

$\overline{v_f}$ = 55.4 -

-0.030	×	Flow of vehicles in the opposite direction of travel, per hour.
-0.004	×	Number of pedestrians crossing the street or walking on the pavement per hour and kilometre.

Average travel speed data from the simulator study produced the following significant results ($p<0.05$) with a R2 value of the analysis of 0.48 (Equation 4:2). The side-friction events in the driving simulator cases were measured over 100 metres of travel.

Average free-flow speed, driving simulator study (4:2)

$\overline{v_f}$ = 40.9 -

- 19.0	×	Number of encountered groups of pedestrians crossing at cross-walks per 100 m of travel
- 1.6	×	Number of encountered groups of pedestrians walking on the pavement (right-hand side) per 100 m of travel
- 14.0	×	Number of groups of buses at bus stop per 100 m of travel
+ 2.4	×	Number of encountered vehicles in the opposite direction per 100 m of travel
- 2.3	×	Gender of the test driver (female =1, male= 0)

The observed average travel speed of all subjects driving the simulator validation scenario was 42.2 km/h, which is close to the free flow speed presented in the equation above. The simulator study showed a considerable impact on the free-flow speed of crossing pedestrians (-19.0 km/h) and buses stopped at the side of the street (-14.0 km/h). The factor Pedestrians walking on the pavement, right-hand side, decreased the free-flow speed by less than 2 km/h. Oncoming traffic in the simulator increased the free-flow speed by 2.4 km/h. Gender was an influential factor on the speed driven in the simulator. In general, the analysis showed that men drove 2.3 km/h faster than women on this street type.

4.1.3 Influence on vehicles' speed profiles of interaction with other road users

Individual driver behaviour data was collected in the field and by means of a driving simulator. Both studies were of unrestrained travel, i.e. free-flow travel.

Speed profiles of observed vehicles upstream of a crosswalk on an urban street in the area wide video data collection are shown in Figure 4:1. Initial vehicle speeds ranged from 30 to 50 km/h. The speed reduction started approximately 45 metres in advance if a pedestrian approached to cross, and dropped on average to approximately 20 km/h or less. The vehicles stopped on average 5 metres ahead of the crosswalk. In the cases when pedestrians did not use their right of way and waited on the side of the street before starting to cross, the observed speed past the crosswalk was on average reduced by 9 km/h.

Speed profiles of drivers passing an occupied bus stop were collected in the driving simulator study. Figure 4:2 illustrates the speed profiles of vehicles at this event. The speed reduction, determined based on graphical analysis, was approximately 10 km/h. Differences in female and male behaviour for this event are commented in section 4.1.4.

Speed data of vehicles passing a side street where there was a vehicle waiting to cross were gathered from the area-wide video data collection (Figure 4:3). Analysis of that specific speed data and studies conducted by Dannelind and Wendel (2003) showed that the speed reduction of vehicles passing an occupied side street approach was approximately 1 km/h.

The speed profiles for different side-friction events were compared graphically with profiles collected at other field study sites.

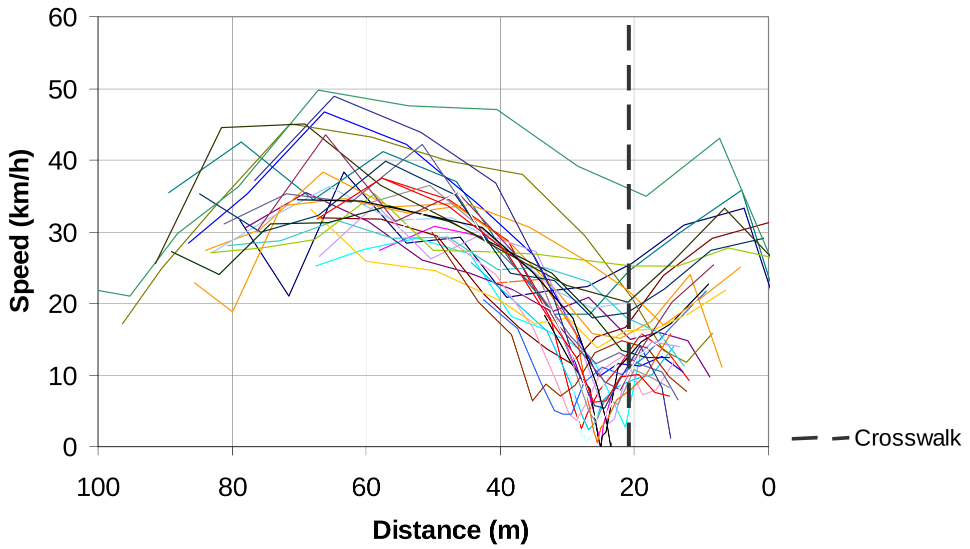


Figure 4:1 Speed profiles of observed vehicles upstream of a crosswalk on an urban street, when pedestrians approach to cross, measured in the field study.

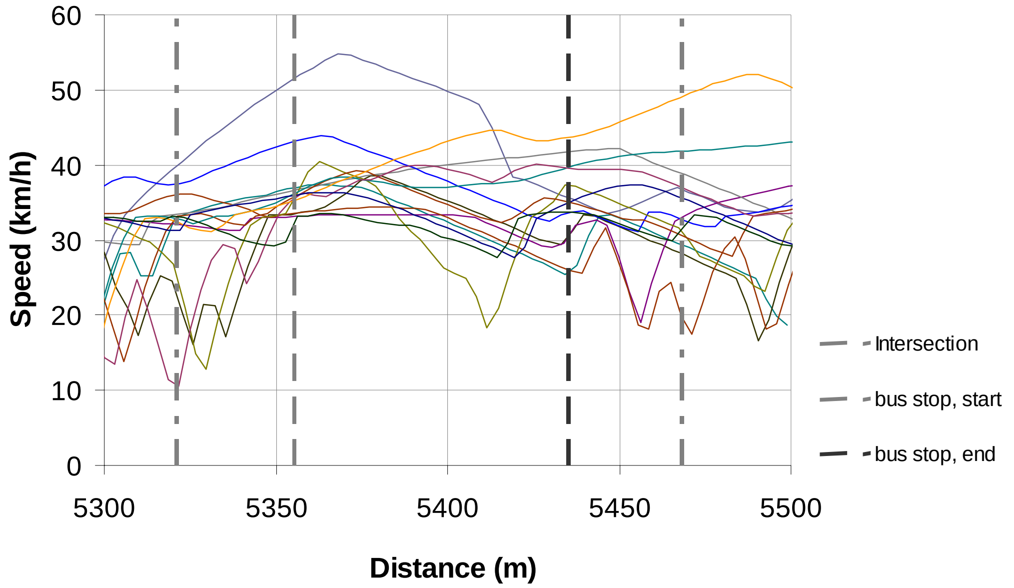


Figure 4:2 Speed profiles of drivers passing an occupied bus stop, collected in the driving simulator study.

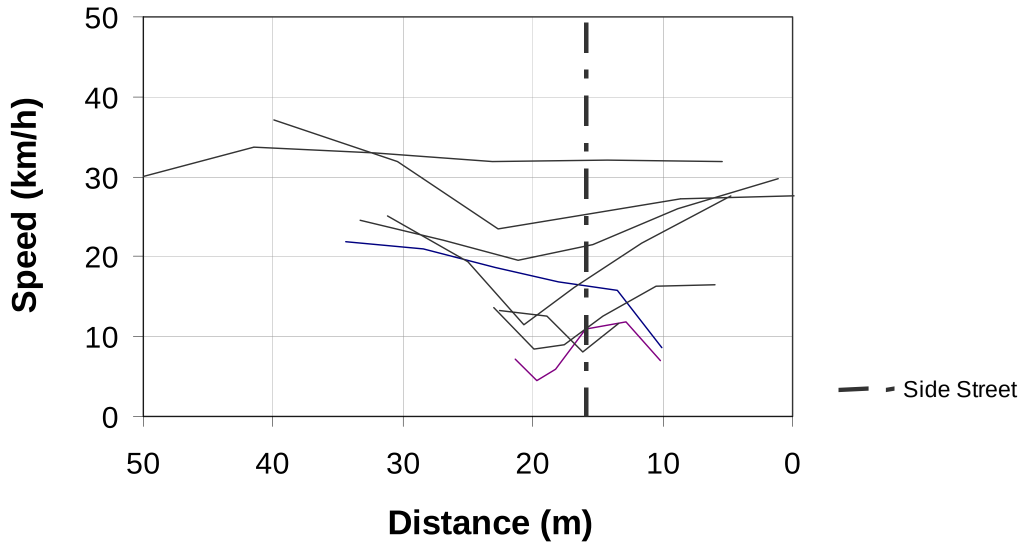


Figure 4:3 Speed profiles of vehicles passing a side street where there was a waiting vehicle, collected in the field study.

4.1.4 Male and female speed profiles

Speed profiles of thirty-nine drivers were collected in the driving simulator study. The drivers encountered many types of side-friction events, of which two reduced their speed significantly: interactions with pedestrians crossing the street and passing buses stopped at a bus stop.

The effect of pedestrians crossing the street at the chosen speed was also observed in the field study, which made it possible to compare speed profiles collected with the two techniques. Speed profiles collected in the simulator study upstream of a crosswalk with pedestrians approaching to cross are presented in Figure 4:4 for male drivers, and in 4:5 for female drivers. Initial vehicle speeds approaching a crosswalk in the simulator ranged from 25 to 50 km/h. The speed started to drop approximately 60 metres prior to the crosswalk if a pedestrian approached to cross, and was reduced to around 30 km/h or less if the pedestrian was given right of way. The vehicles stopped on average 20 metres ahead of the crosswalk in the driving simulator. Several of the subjects expressed difficulties estimating distance to the crosswalk when driving in the simulator and therefore stopped earlier than in reality.

Graphical comparison of speed profiles of simulated and observed behaviour for the event of a pedestrian approaching a crosswalk showed good resemblance, and did not differ notably between male and female drivers.

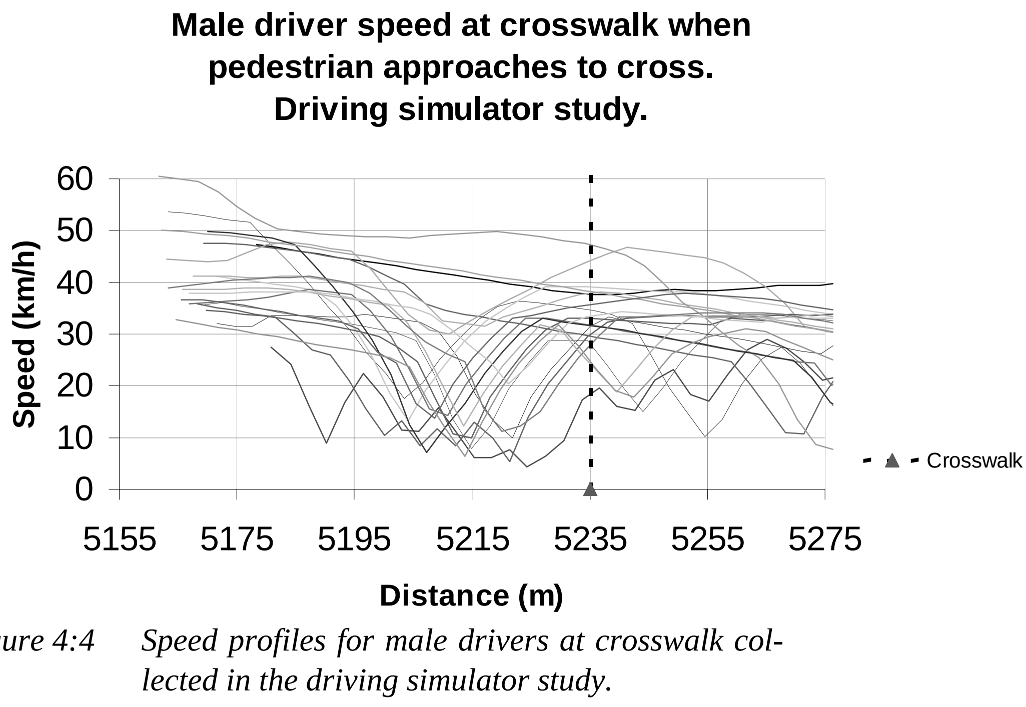


Figure 4:4 Speed profiles for male drivers at crosswalk collected in the driving simulator study.

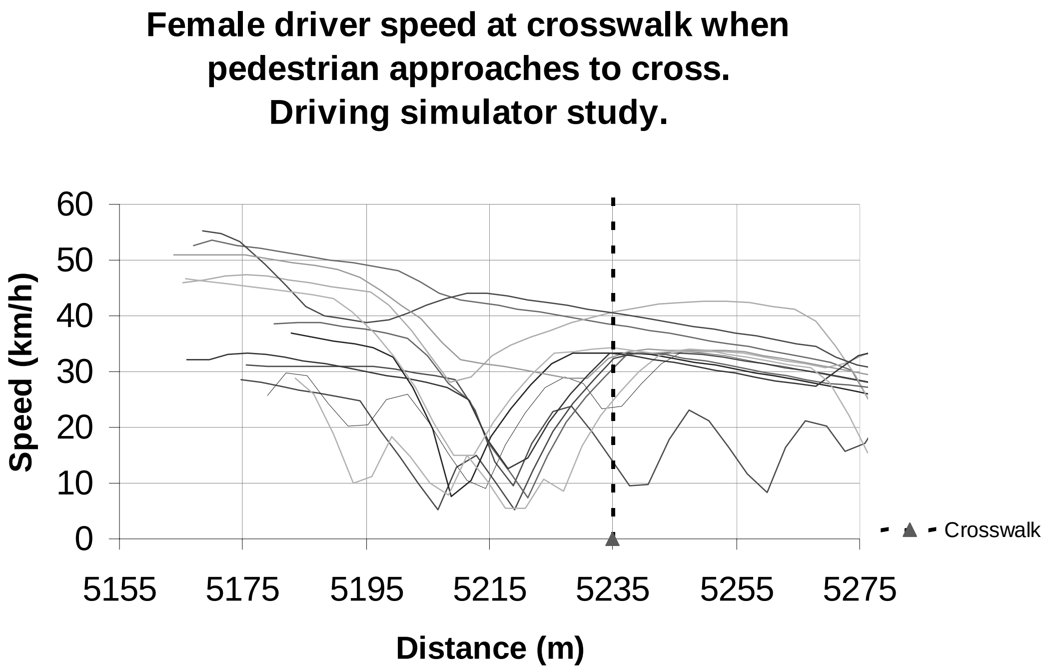


Figure 4:5 Speed profiles for female drivers at crosswalk collected in the driving simulator study.

Driver behaviour when passing an occupied bus stop was also investigated using the driving simulator data. The lane width of the street in this scenario was 3.5 metres. The buses at the bus stop were positioned 3.9-4.1 metres from the centre line in the experiment in accordance with observations from the field study. The speed profiles for men are illustrated in figure 4:6 and for women in figure 4:7. The chosen speeds past the bus stop area illustrated in the figures were notably higher for men than women in this study and this was verified by equations 4:7 and 4:8 in section 4.2.4.

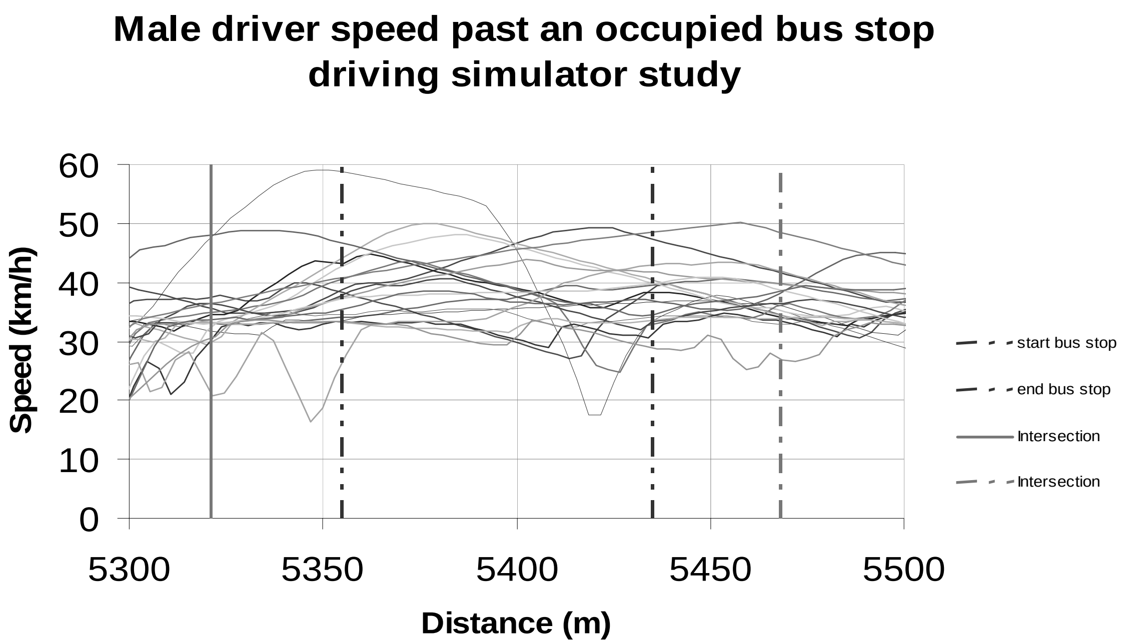


Figure 4:6 *Speed profiles for male drivers passing an occupied bus stop. Collected in the driving simulator study.*

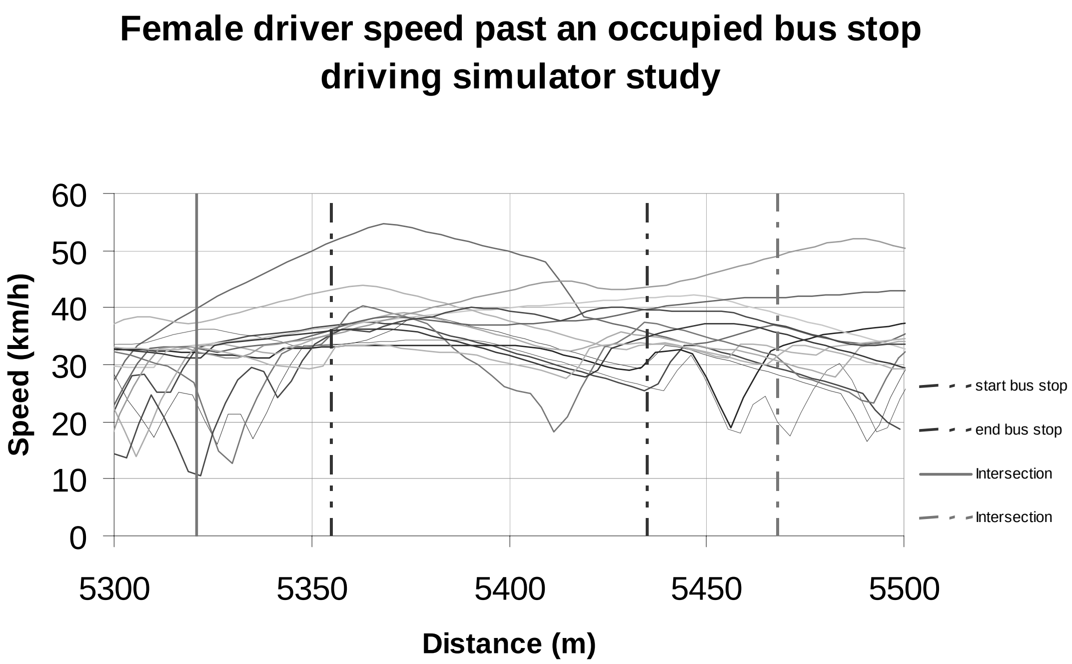


Figure 4:7 *Speed profiles for female drivers passing an occupied bus stop. Collected in the driving simulator study.*

4.2 MACRO STUDY OF TRAFFIC CHARACTERISTICS

4.2.1 Reduced data material

The reduction of the short-base data was performed with support of Nordstrom (2006). The work resulted in three databases with the following content:

1) Short-base data of individual vehicle traffic characteristics for each site (e.g. passage time, vehicle type, direction of travel, headway and spot speed). Peak hours were identified. Driver gender information was included for defined time periods and sites. Aggregation into five minute averages of traffic flow and space mean speed per site was also performed for all of the material.

2) Short-base data consisting of five-minute average speed and flow observations divided into flow classes and supplemented with site characteristics.

3) Aggregated short-base data of average peak hour speed and traffic volume per direction of travel, site characteristics and ratio of vehicles passing through the long-base study area. Performed for street sites with a posted speed limit of 50 km/h.

The long-base study results were stored in another database as described below.

4) Individual travel times and average travel speeds along the long-base routes.

These databases constituted the foundation for calculation of the macro traffic characteristics presented below. The results are presented in the same order as the data bases; first on individual vehicle level, then aggregated into five minute averages followed by aggregation in 60 minute averages. The studies were primarily of streets with the posted speed limit of 50 km/h. Analysis of arterials with the posted speed limit of 70 km/h are reported on in the work by Nordstrom (2006).

4.2.2 Male and female driver behaviour

Computed traffic measures

Traffic characteristics for vehicles passing the selected short-base stations were analysed for the chosen time periods (Aronsson 2006). The results for men and women driving cars or vans were compared per site for the following seven driver behaviour parameters.

Average free-flow speed, male and female driver. The measure represents chosen speed during travel unrestrained by vehicles ahead in the driven direction.

Percentage of male/female drivers leading a platoon. The measure indicates if there was a male or female predominance to drive as platoon leaders. The share of male drivers leading a platoon was calculated and compared to the share of female drivers leading a platoon. Drivers who were unrestrained by a vehicle ahead, but were closely followed by a vehicle behind, were studied.

Average speed of platoon leaders (male/female). The parameter represents the speed choice of an unrestrained driver who is closely followed by one or more vehicles.

Percentage of male/female drivers being restrained by a vehicle ahead. The measure explains if there was a male or female predominance to be hindered by vehicles in front of them and to drive in a queue.

Average headway of restrained drivers, Average time distance to the vehicle behind, restrained traffic and *Average speed of restrained drivers.* These measures represent drivers driving in restrained flows.

Over 3,200 unrestrained vehicles were analysed and the selection criteria was a headway of 5 seconds or more. Review of video recordings and log data induced the decision that a headway greater than 3 seconds represented unrestrained travel and was applied for the study of platoon leaders. The time distance to the vehicle following a platoon leader was defined as 2 seconds or less. A headway less than 2.5 seconds defined restrained traffic in this analysis which covered 1,400 vehicles. The measures average speed, headway and time distance were analyzed to find out if there were any significant differences between male and female driving behaviour. Arithmetic means of the measures were computed and presented as the average values of Tables 4:2 to 4:5. A weighted average figure was computed per road type with the purpose of summarizing the findings.

Results

The results showed no significant difference in mean free-flow speed between male and female drivers (Table 4:2). For a number of studied sites there was an indication of slightly higher female free-flow speeds. The difference in share of men driving as a platoon leader compared to women was small (Table 4:3). On suburban streets there was an indication that the likelihood for men to lead a platoon was slightly higher, although the data supporting this was very limited. On average, male and female platoon leaders maintained speeds which did not differ (Table 4:4). Male and female drivers maintained average time headway to the vehicle in front when driving in a platoon which did not differ. Female drivers were slightly more often represented among restrained drivers in off-peak travel on the arterial road sites (Table 4:5).

Table 4:2 Average free-flow speed, male and female drivers.

Road Type	*Road site*	*Road Geometry*	*Time*	*Average speed (km/h)*			*Number of subjects*		*Two-way flow/ hour*
				Male	*Female*	*Differ-ence*	*Male*	*Fe-male*	
Arterial	**Orby Boulevard** Eastbound Site Monday Str.	4 lane 2-way divided	08.30 – 09.30	*54.0 ± 1.3* *two lane traffic, uncertainty*	*52.3 ± 3.2* *two lane traffic, uncertainty*		338	53	750
	Malmslatts Road Eastbound Site Valla Rotary	2 lanes + 2 transit lanes, 2-way divided	08.30 – 10.30	49.6 ± 0.7	49.8 ± 1.2		241	99	850
	Malmslatts Road Eastbound Site Griftes-garden	2 lanes + 2 transit lanes, 2-way di-vided	08.30 – 10.30	47.1 ± 0.9	47.1 ± 1.6		196	73	850
	Lennings Road Westbound Site Hamn Rotary	2 lane 2-way undivided	08.30 – 10.30, 14.30-16.10	47.5 ± 0.5	48.5 ± 0.8	*sign diff 0.05 level*	489	161	400
			Peak 07.30 – 08.30	–	–				700
	Weighted average, excl Orby			**48.0**	**48.6**	**-0.6**			
Suburban street	**Harads Road** Eastbound, site Stuvsta Rotary	2 lane 2-way undivided	08.30 – 09.00, 12.00 – 13.00	46.4 ± 1.2	44.3 ± 1.8	*sign diff 0.10 level*	107	43	700
	Old Tannefors Road Westbound Site Pelargonium	2 lane 2-way undivided	Peak 15.45 – 16.45, and 16-45-17.15	43.6 ± 1.2	44.3 ± 1.8		114	41	900
	Weighted average			**45.0**	**44.3**	**0.7**			
Urban street	**St Lars Street** Southbound Site Linné	2 lane 2-way undivided	14.50 – 15.50	34.8 ± 1.7	36.9 ± 2.6	*sign diff 0.20 level*	46	27	400
	St Lars Street Southbound, site Folkungavallen	2 lane 2-way undivided	Peak 07.30 – 08.30	46.9 ± 1.3	47.7 ± 1.9		75	33	750
			08.30 – 09.30	45.2 ± 1.5	45.9 ± 1.8		66	34	500
	Brunns Street Eastbound, site Repslagare Str.	2 lane 2-way undivided	06.30 – 10.30	34.8 ± 0.4	34.9 ± 0.5		475	201	550
			Cars and trucks 08.30 – 10.30	34.3 ± 0.6	35.4 ± 0.8	*sign diff 0.10 level*	252	92	800
	Weighted average			**36.4**	**37.2**	**-0.8**			

Table 4:3 Percentage of male/female drivers leading a platoon.

Road Type	Road site	Road Geometry	Time	Percentage		
				Male	*Female*	*Differ-ence in units*
Arterial	**Orby Boulevard** Eastbound Site Monday Street	4 lane 2-way divided	08.30 – 09.30	–	–	
	Malmslatts Road Eastbound Site Valla Rotary	2 lanes + 2 transit lanes, 2-way divided	08.30 – 10.30	11 %	15 %	
	Malmslatts Road Eastbound Site Griftesgarden	2 lanes + 2 transit lanes, 2-way divided	08.30 – 10.30	12 %	14 %	
	Lennings Road Westbound Site Hamn Rotary	2 lane 2-way undivided	08.30 – 10.30, 14.30-16.10	10 %	8 %	
			Peak 07.30 – 08.30	12 %	11 %	
	Weighted average			**11 %**	**11 %**	**0 %**
Suburban street	**Harads Road** Eastbound Site Stuvsta Rotary	2 lane 2-way undivided	08.30 – 09.00, 12.00 – 13.00	9 %	4 % *small sample*	
	Old Tannefors Road Westbound Site Pelargonium	2 lane 2-way undivided	Peak 15.45 – 16.45, and 16.45-17.15	9 %	6 % *small sample*	
	Weighted average			**9 %**	**5 %**	**4 %**
Urban Street	**St Lars Street** Southbound at Site Linné	2 lane 2-way undivided	14.50 – 15.50	3 % *small sample*	3 % *small sample*	
	St Lars Street Southbound site Folkungavallen	2 lane 2-way undivided	Peak 07.30 – 08.30	-	-	
			07.30 – 09.30	8 %	6 %	
	Brunns Street Eastbound site Repslagare Str.	2 lane 2-way undivided	06.30 – 10.30	9 %	9 %	
			Peak 07.30 – 08.30	-	-	
	Weighted average			**8 %**	**8 %**	**0 %**

Table 4:4 Average speed of platoon leaders.

Road Type	***Road site***	***Road Geometry***	***Time***	***Average speed (km/h)***			***Number of subjects***		***Two-way flow/ hour***
				Male	***Female***	***Difference***	***Male***	***Female***	
Arterial	**Orby Boulevard** Eastbound Site Monday Str.	4 lane 2-way divided	08.30 – 09.30	–	–	–	–	–	750
	Malmslatts Road Eastbound Site Valla Rotary	2 lanes + 2 transit lanes, 2-way divided	08.30 – 10.30	47.5	46.8		58	31	850
	Malmslatts Road Eastbound Site Griftesgarden	2 lanes + 2 transit lanes, 2-way divided	08.30 – 10.30	46.5	44.3	*sign. diff 0.05 level*	67	29	850
	Lennings Road Westbound Site Hamn Rotary	2 lane 2-way undivided	08.30 – 10.30, 14.30-16.10 Peak 07.30 – 08.30	46.0 46.1	46.2 47.0		115 26	32 10	400 700
	Weighted average (excl peak)			**46.5**	**45.8**	**0.7**			
Suburban street	**Harads Road** Eastbound Site Stuvsta Rotary	2 lane 2-way undivided	08.30 – 09.00, 12.00 – 13.00	42.7	44.8 *small sample*		17	3	700
	Old Tannefors Road Westbound Site Pelargonium	2 lane 2-way undivided	Peak 15.45 – 16.45, and 16.45-17.15	42.0	40.7 *small sample*		21	4	900
	Weighted average			**42.3**	**42.5**	**-0.2**	38	7	
Urban Street	**St Lars Street** Southbound at Site Linné	2 lane 2-way undivided	14.50 – 15.50	*small sample*	*small sample*		2	1	400
	St Lars Street Southbound site Folkungavallen	2 lane 2-way undivided	Peak 07.30 – 08.30 07.30 – 09.30	- 48.1	- 45.6 *small sample*		- 17	- 7	750 500
	Brunns Street Eastbound site Repslagare Str.	2 lane 2-way undivided	06.30 – 10.30 Peak 07.30 – 08.30	32.5 -	33.8 -		66 -	32 -	550 800
	Weighted average			**35.7**	**35.9**	**-0.2**	83	39	

Table 4:5 Percentage of male/female drivers being restrained by vehicle ahead.

Road Type	*Road site*	*Road Geometry*	*Time*	*Percentage*		
				Male	*Female*	*Difference in units*
Arterial	**Orby Boulevard** Eastbound Site Monday Str.	4 lane 2-way divided	08.30 – 09.30	–	–	
	Malmslatts Road Eastbound Site Valla Rotary	2 lanes + 2 transit lanes, 2-way divided	08.30 – 10.30	27 %	30 %	
	Malmslatts Road Eastbound Site Griftesgarden	2 lanes + 2 transit lanes, 2-way divided	08.30 – 10.30	45 %	49 %	
	Lennings Road Westbound Site Hamn Rotary	2 lane 2-way undivided	08.30 – 10.30, 14.30-16.10	18 %	20 %	
			Peak 07.30 – 08.30	27 %	27 %	
	Weighted average			**27 %**	**30 %**	**- 3 %**
Suburban street	**Harads Road** Eastbound Site Stuvsta Rotary	2 lane 2-way undivided	08.30 – 09.00, 12.00 – 13.00	23%	19 %	
	Old Tannefors Road Westbound Site Pelargonium	2 lane 2-way undivided	Peak 15.45 – 16.45, and 16.45-17.15	28 %	19 %	
	Weighted average			**26 %**	**19 %**	**7 %**
Urban Street	**St Lars Street** Southbound Site Linné	2 lane 2-way undivided	14.50 – 15.50	9%	18 %	
	St Lars Street Southbound site Folkungavallen	2 lane 2-way undivided	Peak 07.30 – 08.30	-	-	
			07.30 – 09.30	17 %	19 %	
	Brunns Street Eastbound site Repslagare Str.	2 lane 2-way undivided	06.30 – 10.30	16 %	14 %	
			Peak 07.30 – 08.30	-	-	
	Weighted average			**16 %**	**16 %**	**0.5 %**

4.2.3 Influence on space mean speed of street characteristics and side-friction factors

Multiple regression analysis of observed space mean speed was performed for the studied streets with a posted speed limit of 50 km/h. The investigated independent variables were

- Observed average flow in the studied direction per 5 min,
- Average number of crossing pedestrians and cyclists per 15 min and 400 m,
- Street function (thoroughfare or approach = 0; other link in main network = 1)
- Number of lanes in the studied direction
- Bicycle lane indicator (yes/no),
- Parking indicator (yes/no),
- Bus stop indicator (yes/no) and
- Minor intersections per 1 km.

The following variables were also analysed but were found to be non-significant and are therefore not included in the variable lists on the next pages;

- Median (yes/no),
- Structure of the environment (urban=0; suburban=1)
- Distance to upstream intersection (m) and
- Lane width (m).

The ranges of the independent variables are listed in Table 4:6. The obtained speed models of the analysis are presented in equations 4:3 to 4:6. The significant results and model summary for the multiple regression analysis are shown in tables 4:7 to 4:10. The applied level of significance was $p < 0.05$.

Table 4:6 The ranges of variable used in the multiple regression analysis of space mean speed.

Variable		**Min and max range for**			
		Arterials	Suburban streets	Urban streets	All street types
Flow	Flow in studied direction per 5 min	5-97	2-67	3-87	2-97
Ped	Average number of crossing pedestrians and cyclists per 15 min and 400 m	5-25	5-15	15-25	5-25
Func	Street function	0 or 1	0 or 1	1	0 or 1
Lanes	Number of lanes in the studied direction	2	1 or 2	1 or 2	1 or 2
BicSep	Bicycle lane indicator	1	0 or 1	0 or 1	0 or 1
Park	Parking indicator	0	0	0 or 1	0 or 1
Bus	Bus stop indicator	0 or 1	0 or 1	0 or 1	0 or 1
Inter	Intersections per 1 km	0-6	0-5	1-10	0-10
	Median	1	0	0	0 or 1
	Structure of the environment	0 or 1	0 or 1	0	0 or 1
	Distance to the upstream intersection	45-104	41-500	15-227	15-500
	Lane width	7.0-8.5	3.5-6.0	3.5-7.5	3.5-8.5

Arterials

The resulting space mean speed model for arterials was:

$$\bar{v}_{obs} = 63.8 - 0.087 \times Flow - 8.61 \times Func - 2.44 \times Inter \qquad (4:3)$$

where

$\bar{v}_{obs}$	=	Observed space mean speed (km/h)
Flow	=	Observed average traffic flow in the studied direction of travel expressed in vehicles per 5 min
Func	=	Street function (thoroughfare or approach = 0; other link in main network = 1)
Inter	=	Number of minor intersections per 1 km

Table 4:7 Output of the multiple regression analysis of arterials with the posted speed limit of 50 km/h.

	Unstandardized Coefficients	Standardized Coefficients	t-value	Sig.
	B	Beta		
(Constant)	63.760		23.373	.000
Flow	-0.087	-0.273	-2.657	.011
Func	-8.609	-0.655	-6.376	.000
Inter	-2.438	-0.438	-4.313	.000

Model summary		ANOVA	
R^2	Std. Error of the Estimate	F	Sig.
0.517	4.73	17.455	0.000

The variables Observed average traffic flow, Street function and Number of intersections per 1 km exhibited significant impact on the observed space mean speed of arterials. The variables Average number of crossing pedestrians and cyclists and Bus stop indicator were non-significant. Three variables were unvaried for the street type: Number of lanes in the studied direction, Bicycle lane indicator and Parking indicator. The R2 value of the model for arterial streets was 0.52.

Suburban streets

The resulting space mean speed model for suburban streets was:

$$\bar{v}_{obs} = 55.9 - 0.072 \times Flow - 0.414 \times Ped - 5.30 \times Func + 5.80 \times Lanes - 3.83 \times Bus \qquad (4:4)$$

where

$\bar{v}_{obs}$	=	Observed space mean speed (km/h)
Flow	=	Observed average traffic flow in the studied direction of travel, expressed in vehicles per 5 min
Ped	=	Average number of crossing pedestrians and cyclists (summarized in groups of 5, 15 and 25 people per 15 min and 400 m)
Func	=	Street function (thoroughfare or approach = 0; other link in main network = 1)
Lanes	=	Number of lanes in the studied direction (1 or 2).
Bus	=	Roadside bus stop exists on link (yes=1; no=0)

Table 4:8 Output of the multiple regression analysis of suburban streets.

	Unstandardized Coefficients	Standardized Coefficients	t-value	Sig.
	B	Beta		
(Constant)	55.857		45.381	.000
Ped	-0.414	-0.354	-7.255	.000
Func	-5.301	-0.367	-8.250	.000
Bus	-3.832	-0.329	-6.959	.000
Lanes	5.798	0.311	6.804	.000
Flow	-0.072	-0.191	-4.335	.000
Model summary		ANOVA		
R^2	Std. Error of the Estimate	F	Sig.	
0.650	3.440	71.769	0.000	

Most of the independent variables showed significant impact on the observed space mean speed for suburban streets. The variables Bicycle lane indicator and Parking indicator were unvaried for the street type. The variable Intersections per 1 km was non-significant. The R2 value was 0.65.

Urban streets

The resulting space mean speed model for urban streets was as follows:

$$\bar{v}_{obs} = 39.8 - 0.202 \times Flow - 0.237 \times Ped + 5.24 \times Lanes + 4.73 \times BicSep - 5.54 \times Park \quad (4:5)$$

where

$\bar{v}_{obs}$	=	Observed space mean speed (km/h)
Flow	=	Observed average traffic flow in the studied direction of travel, expressed in vehicles per 5 min
Ped	=	Average number of crossing pedestrians and cyclists (summarized in groups of 5, 15 and 25 people per 15 min and 400 m)
Lanes	=	Number of lanes in the studied direction (1 or 2).
BicSep	=	Separated bicycle lane (yes=1; no = 0)
Park	=	Roadside parking permitted (yes=1; no=0)

Table 4:9 Output of the multiple regression analysis of urban streets.

	Unstandardized Coefficients	Standardized Coefficients	t-value	Sig.
	B	Beta		
(Constant)	39.775		14.156	.000
Flow	-0.202	-0.529	-9.011	.000
Ped	-0.237	-0.216	-2.350	.020
Lanes	5.238	0.284	3.094	.002
BicSep	4.730	0.425	4.995	.000
Park	-5.542	-0.358	-3.866	.000
Model summary		ANOVA		
R^2	Std. Error of the Estimate	F	Sig.	
0.658	3.27	45.339	0.000	

A majority of the studied variables were included in the space mean speed model for urban streets for which the R2 value was 0.66. One variable was unvaried for the street type; Street function. The variables Bus stop indicator and Intersection per 1 km were non-significant.

All street types combined

The resulting space mean speed model for all street types was:

$$\bar{v}_{obs} = 60.2 - 0.121 \times Flow - 0.619 \times Ped - 5.42 \times Func + 3.11 \times Lanes - $$
$$- 6.13 \times Park - 0.60 \times Inter \qquad (4:6)$$

where

$\bar{v}_{obs}$	=	Observed space mean speed (km/h)
Flow	=	Observed average traffic flow in the studied direction of travel, expressed in vehicles per 5 min
Ped	=	Average number of crossing pedestrians and cyclists (summarized in groups of 5, 15 and 25 people per 15 min and 400 m)
Func	=	Street function (thoroughfare or approach = 0; other link in main network = 1)
Lanes	=	Number of lanes in the studied direction (1 or 2)
Park	=	Roadside parking permitted (yes=1; no=0)
Inter	=	Number of minor intersections per 1 km

Table 4:10 Output of the multiple regression analysis of all street types.

	Unstandardized Coefficients	Standardized Coefficients	t-value	Sig.
	B	Beta		
(Constant)	60.232		53.988	.000
Flow	-0.121	-0.229	-7.954	.000
Ped	-0.619	-0.530	-13.380	.000
Func	-5.422	-0.243	-8.303	.000
Lanes	3.112	0.152	4.999	.000
Park	-6.133	-0.153	-4.939	.000
Inter	-0.599	-0.166	-4.383	.000
Model summary		ANOVA		
R^2	Std. Error of the Estimate	F	Sig.	
0.717	4.611	155.5	0.000	

For all street types combined it was shown (Equation 4:6 and Table 4:10) that Observed average flow in the studied direction, Average number of crossing pedestrians and cyclists, Street function, Number of lanes in the studied direction, Parking indicator and Intersections per 1 km exhibited significant impact on the studied speed measure. The factor Bus stop indicator was not significant. The R2 value was 0.72. The results are similar to the findings of a study of operating speed models for urban speed tangents (Wang, Dixon, Li et al. 2006) proving Number of lanes in the studied direction to be the most significant influence on speed, in the outlined analysis excluding traffic flow. The variables Number of intersections per km and Parking indicator were also significant in that study.

4.2.4 Travel time studies

Driver populations in general

Travel times of nine long-base routes, both directions of travel, were obtained from the passage times collected at the entry and exit short-base stations for vehicles with an odd last digit in their number plate. Figure 4:8 illustrates an example of travel times for the investigated vehicles on one route. The results of travel time calculations on the investigated routes for both directions of travel during peak hour and off-peak hours are shown in Tables 4:11 to 4:13. Information on confidence interval ($p<0.05$), number of investigated vehicles, two-way traffic flow per hour and the number of delay spots (e.g. at major intersections) is also given in the tables. Delays at the delay spots are included in the travel times.

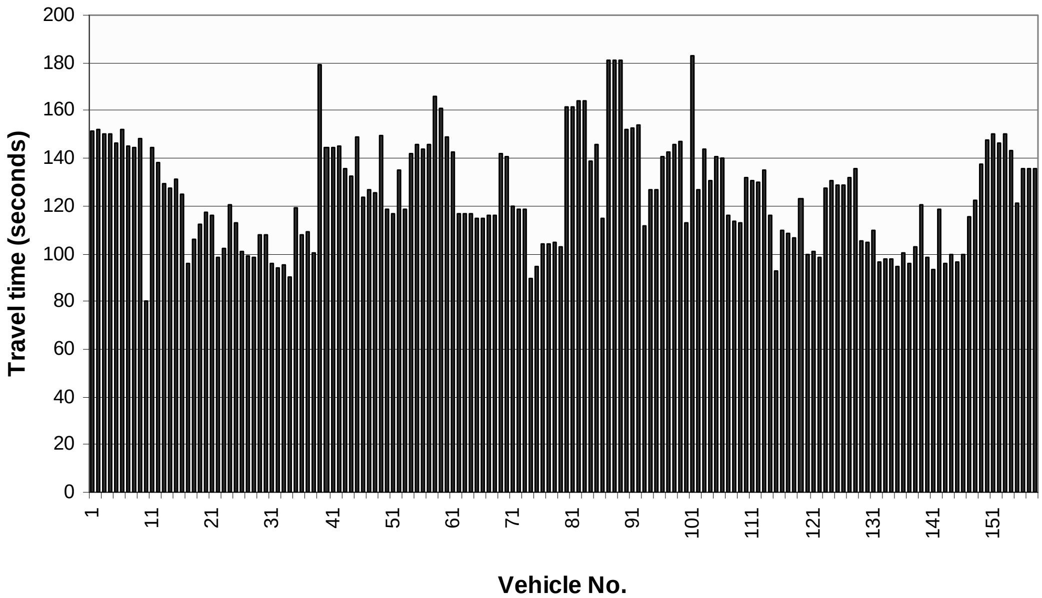


Figure 4:8 Example of travel times of through vehicles from Old Tannefors Road, northbound, afternoon peak hour.

The average travel speed on the studied arterial ranged from 30 to 37 km/h (Table 4:11). The average travel speeds on the suburban streets ranged from 35 to 50 km/h (Table 4:12). The through vehicles on the investigated urban streets travelled with an average travel speed ranging from 27 to 52 km/h (Table 4:13).

The results of this section and section 4.2.2 demonstrated that speed choice and driver behaviour were consistent for the selected street types regardless of city type and population.

Table 4:11 Average travel speed on the arterial long-base routes, peak hours and off-peak hours.

Town	*Streets included in the route*	*Time*	*Average speed (km/h)*	*Confi-dence-interval / 2*	*Number of investi-gated vehicles*	*Two-way flow/ hour*	*No of delay spots*
Linkoping	**Malmslatts Road**	08.30 – 09.30	36.9	±0.6	111	850	3
	Westbound	16.30 – 17.30	31.8	±0.5	195	1550	
	Malmslatts Road	07.30 – 08.30	32.8	±0.4	249	1350	
	Eastbound	08.30 – 09.30	36.3	±0.6	127	850	
		16.30 – 17.30	30.4	±0.3	255	1550	

Table 4:12 Average travel speed on the suburban long-base routes, peak and off-peak hours.

Town	*Streets included in the route*	*Time*	*Average speed (km/h)*	*Confi-dence-interval / 2*	*Number of investi-gated vehicles*	*Two-way flow/ hour*	*No of delay spots*
Stockholm	**Kvarnbacks Road**	07.30 – 08.30	42.2	±0.4	118	850	0
	Westbound	09.00 – 10.00	44.7	±0.4	124	800	
	Kvarnbacks Road	07.30 – 08.00	40.0	±0.4	137	850	
	Eastbound	09.00 – 10.00	45.1	±0.4	88	800	
	Harads Road	07.30 – 08.30	46.6	±0.6	52	700	0
	Northbound	12.00 – 13.00	45.8	±0.3	87	700	
	Harads Road	07.30 – 08.30	47.8	±0.6	40	700	
	Southbound	12.20 – 13.00	44.9	±0.4	54	700	
Linkoping	**Old Tannefors Road**	09.00 – 10.00	45.3	±0.6	68	600	0
	Northbound	15.45 – 16.45	40.1	±0.6	158	900	
	Old Tannefors Road	09.00 – 10.00	46.7	±0.9	27	600	
	Southbound	15.45 – 16.45	42.0	±0.6	105	900	
Nykoping	**Lennings Road** Northbound	07.00 – 07.30, 08.30 – 09.00	50.1	±1.5	20	400	1
		16.10 – 17.10	44.9	±0.7	42	750	
	Lennings Road Southbound	07.00 – 07.30, 08.30 – 09.00	48.0	±0.8	21	400	
		16.10 – 17.10	47.3	±0.9	38	750	
	Angstuge Road	07.30 – 08.30	35.0	±0.4	59	300	0
	Westbound	08.30 – 09.00	37.0	±1.2	18	200	
	Angstuge Road	07.30 – 08.30	36.3	±0.6	16	300	
	Eastbound	08.30 – 09.00	37.4	±1.2	18	200	

Table 4:13 Average travel speed on the urban long-base routes, peak hours and off-peak hours.

Town	Streets included in the route	Time	Average speed (km/h)	Confi-dence-interval / 2	Number of investi-gated vehicles	Two-way flow/ hour	No of delay spots
Stockholm	**Nytorgs Street**	14.30 – 15.30	28.5	±0.5	140	400	0
	Southbound	15.30 – 16.30	26.9	±0.5	176	400	
Linkoping	**St Lars Street**	07.30 – 08.30	27.2	±0.5	24	750	1
	Southbound	08.30 – 09.30	33.1	±1.3	30	500	
		16.00 – 17.00	34.4	±0.7	78	800	
	St Lars Street	07.30 – 08.30	29.6	±0.6	88	750	
	Northbound	08.30 – 09.30	32.8	±0.9	52	500	
		16.00 – 17.00	30.5	±0.7	65	800	
Nykoping	**Brunns Street**						
	Repslagare Street –	07.30 – 08.30	30.8	±0.7	43	800	1
	Brunns Street	08.30 – 09.30	35.9	±0.8	26	550	
	Repslagare Street -	07.30 – 08.30	28.8	±0.8	34	800	
	East Rund Street	08.30 – 09.00	33.9	±0.8	24	550	
	Brunns Street -	07.30 – 08.30	31.1	±0.8	22	800	
	East Rund Street	08.30 – 09.30	52.0	±4.2	14	500	
	East Rund Street -	07.30 – 08.30	36.0	±0.8	27	800	
	Brunns Street	08.30 – 09.30	39.1	±0.8	11	500	

The average travel speed on long-base routes for each street type was studied with the variable two-way traffic flow (Figure 4:9). The data was dispersed and a linear function could not be calculated for all streets combined (R square below 0.05). Division by street type provides less speed variance for arterials (R square over 0.90).

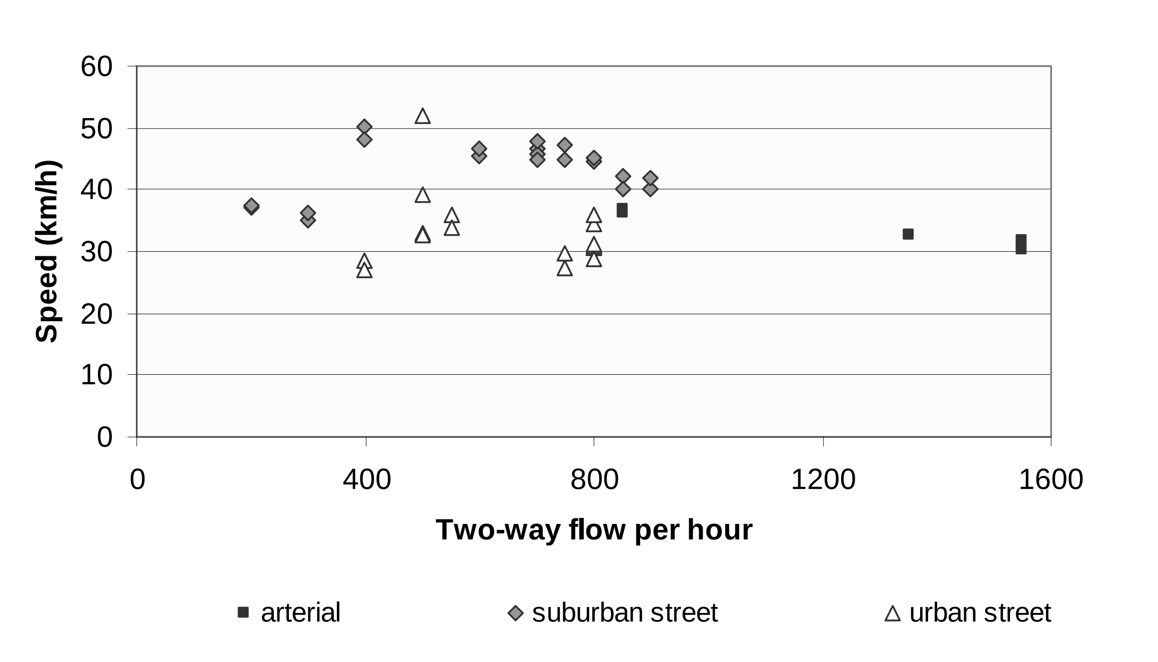


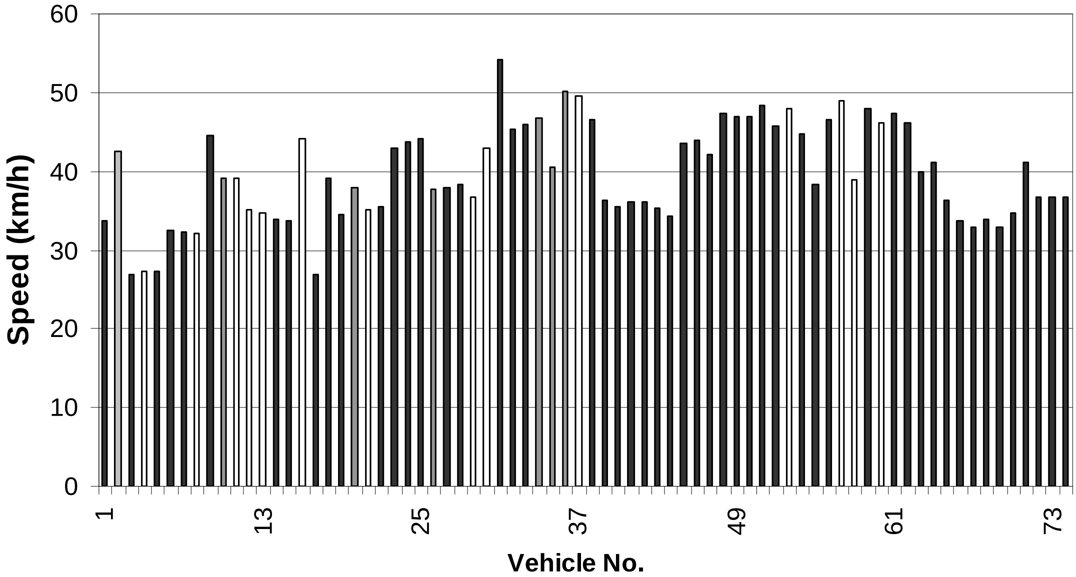
Figure 4:9 Study of average travel speed and traffic flow of the long-base routes.

Ratio of vehicles passing through a long-base study area

The percentage of vehicles passing through the long-base study area were calculated to investigate, combined with other traffic and site variables, if the variable had a significant impact on speed. Multiple regression analysis was performed for the ratio of vehicles passing through the study area, traffic flow and site specific data collected at 30 short-base stations during peak hour. The dependent variable was space mean speed during peak hour. The analysis was made for each street type and all streets combined. The analysis demonstrated that the factor ratio of vehicles passing through the long-base study area was not significant ($p<0.05$). For the urban street model, the variable structure of the environment (1=urban, 0=suburban) had a significant influence (value of –7.9 km/h). The constant value of the urban street model was 42.3 km/h and R2 value was 0.52. The R2 values for the other street types were 0.3 and less. In conclusion, the variable ratio of vehicles passing through a long-base study area did not influence speed.

Results from the field study of male and female average travel speeds

Information on the gender of the drivers of the through vehicles was extracted for one of the routes to compare male and female driving behaviour. The selected route was a sub-urban street, Old Tannefors Road, and the time period was from 16.15 to 16.45 during the afternoon peak hour. The design of the street was two lane, two-way undivided traffic, and narrow pavements for pedestrians. The posted speed limit was 50 km/h. The studied direction of the route was northbound towards the city centre. The registration numbers of vehicles with an odd last digit were noted together with the gender of the driver. Women's and men's average travel speed on this long-base route is illustrated in Figure 4:10.



Black = male driver, white = female driver, grey = driver not visible.

Figure 4:10 Average travel speed of through vehicles on a long-base route reported by driver gender.

The speed distribution of female drivers was compared to the whole population. Through vehicles driven by women followed a speed distribution similar to the whole through vehicle population. The average speed of men and women was tested for equality of means. The result proved that the difference in average travel speed of men and women was not significant on the $p< 0.05$ level. These findings, combined with the findings of the short-base study section 4.2.2 lead to the decision that further investigation of travel speeds on more long-base routes would be redundant. No significant difference was found in space mean speed or average travel speed between male and female drivers.

Results from the driving simulator study of male and female average travel speeds

The average travel speed of male and female subjects in the driving simulator was investigated. Regression analysis of the male and female driver populations verified gender differences regarding the impacts of specific side-friction events (Equation 4:7 and 4:8).

Average free-flow speed, male drivers (4:7)

$\overline{v_f}$ = 41.1 -

- 19.5	×	Number of encountered groups of pedestrians crossing at crosswalks per 100 m of travel
- 1.6	×	Number of encountered groups of pedestrians walking on the pavement (right-hand side) per 100 m of travel
- 12.3	×	Number of groups of buses at bus stop per 100 m of travel
+ 2.2	×	Number of encountered vehicles in the opposite direction per 100 m of travel

Average free-flow speed, female drivers (4:8)

$\overline{v_f}$ = 38.4 -

- 18.3	×	Number of encountered groups of pedestrians crossing at crosswalks per 100 m of travel
- 1.5	×	Number of encountered groups of pedestrians walking on the pavement (right-hand side) per 100 m of travel
- 16.0	×	Number of groups of buses at bus stop per 100 m of travel
+ 2.5	×	Number of encountered vehicles in the opposite direction per 100 m of travel

Men had a significantly higher free-flow speed than women when driving in the simulator. The difference was 2 km/h (Equation 4:2) or more according to equations 4:7 and 4:8. The average free-flow speed of male drivers was reduced by 12.3 km/h when passing an occupied bus stop. The equivalent value of female drivers was 16.0 km/h. This implies that women reduced their vehicle speed to a greater extent than men did when passing a bus at bus stop. The difference in reduction of average speed was 4.3 km/h, which the speed profiles in section 4.1.4 also showed.

4.3 CONCLUSIONS

The driver behaviour studies in the micro study identified a number of side-friction events which significantly reduced speed:

- Passing a crosswalk where a pedestrian approaches to cross
- Passing an occupied bus stop
- Passing a side street were a vehicle is waiting to enter the main street

Graphic analysis of speed profiles of observed vehicles upstream of a crosswalk on an urban street showed a 9 km/h vehicle speed reduction for the case where pedestrians did not use their right of way and waited on the side of the street. Graphic analysis of speed profiles of observed vehicles passing a side street where a vehicle is waiting showed that the speed reduction was approximately 1 km/h. The speed reduction of drivers passing an occupied bus stop in the driving simulator was approximately 10 km/h.

The conclusion of the field study of Swedish male and female drivers was that they differed only marginally in their speed and headway driving behaviour. The simulator study showed no difference in behaviour between men and women for the event of arriving at a crosswalk with approaching pedestrians. For the event passing an occupied bus stop men drove 4,3 km/h faster than women on average.

Analysis of speed, flow and site characteristics in macro models showed that the following variables significantly influence observed space mean speed:

- Flow in the studied direction per 5 min
- Average number of crossing pedestrians and cyclists per 15 min and 400 m
- Street function
- Number of lanes in the studied direction
- Parking indicator
- Minor intersections per 1 km

The models of space mean speed for the different street types are summarized in Table 4:14. The abbreviation NS in the table stands for non-significant on the $p<0.05$ level, and a blank coefficient indicates that the variable was unvaried for the street type. All investigated streets had a posted speed limit of 50 km/h. R2 values for all regressions were approximately 0.7. When excluding the factor Average number of crossing pedestrians and cyclists and rerunning the model all streets combined, the explanatory power R2 decreased to the value of 0.58.

The results achieved from the long-base study can be summarized as follows: the ratio of vehicles passing through the long-base study areas did not influence the space mean speed. The average travel speeds on the studied long-base routes were:

- 30 to 37 km/h for arterials,
- 35 to 50 km/h for suburban streets and
- 27 to 52 km/h for urban streets.

Table 4:14 Results of multiple regression space mean speed analysis for urban streets.

Variable		Regression coefficients of the studied street types			
		Arte-rials	Subur-ban streets	Urban streets	All street types
	(Constant)	63.8	55.9	39.8	60.2
Flow	Flow in studied direction per 5 min	-0.087	-0.072	-0.202	-0.121
Ped	Av. number of crossing pedestrians and cyclists per 15 min and 400 m	NS	-0.414	-0.237	-0.619
Func	Street function	-8.61	-5.30		-5.42
Lanes	Number of lanes in the studied direction		5.80	5.24	3.11
BicSep	Bicycle lane indicator			4.73	NS
Park	Parking indicator			-5.54	-6.13
Bus	Bus stop indicator	NS	-3.83	NS	NS
Inter	Intersections per 1 km	-2.44	NS	NS	-0.60
	R2 value	*0.52*	*0.65*	*0.66*	*0.72*

$$\bar{v}_{obs} = Constant - a \times Flow + b \times Ped + c \times Func + d \times Lanes + e \times BicSep + f \times Park + g \times Bus + h \times Inter \quad (4:10)$$

Where

$\bar{v}_{obs}$ = Observed space mean speed (km/h)

Flow = Observed average traffic flow in the studied direction of travel expressed in vehicles per 5 min

Ped = Average number of crossing pedestrians and cyclists (summarized in groups of 5, 15 and 25 people per 15 min and 400 m)

Func = Street function (thoroughfare or approach = 0; other link in main network = 1)

Lanes = Number of lanes in the studied direction (1 or 2).

BicSep = Separated bicycle lane (yes=1; no = 0)

Park = Roadside parking permitted (yes=1; no=0)

Bus = Roadside bus stop exists on link (yes=1; no=0)

Inter = Number of minor intersections per 1 km

a,b,c,d… = Regression coefficients

5. SIMULATION OF THE TRAFFIC PROCESS IN AN URBAN STREET ENVIRONMENT USING A MICROSCOPIC TRAFFIC MODEL

This chapter covers the microscopic traffic simulation study of one urban street for a range of flow conditions and side-friction events.

5.1 METHODOLOGY

5.1.1 Background

The use of microscopic traffic simulation models has, as supported by the literature, a considerable future potential in the field of transportation planning and traffic engineering. Microscopic modelling aims to represent vehicles in a traffic stream and their interactions with other road users and the road infrastructure, and can after careful calibration and validation provide a platform for evaluation of alternative design solutions and traffic parameter values. Simulation of the traffic process in an urban street environment was applied in this research effort to broaden and deepen knowledge regarding the impact on speed for a range of traffic and side-friction conditions obtained from the empirical studies, and to investigate the usefulness of this methodology in a wider traffic planning perspective. The selected microscopic model was enhanced and calibrated to represent the observed driver behaviour on an urban street. Systematic runs of the model were performed for production of speed patterns and speed flow relationships. The runs were performed for a range of traffic flow levels on the major and side streets, and for combinations of bus service and pedestrian flow.

There are a number of microscopic models available and Burghout (2004) gives some examples, viz. AIMSUN/2, VISSIM, CORSIM, MITSIMLab, and Paramics. The VISSIM (PTV 2005) program was selected for the microscopic simulation in the present study based on experience gained within the Department of Transport and Economics, at KTH. The VISSIM model has a Vehicle Actuated Programming (VAP) module, which was used to develop the functionality that enabled the model to represent the observed driver behaviour when exposed to different types of side-friction events. The model reproduces motor vehicle and pedestrian movement as shown in Figure 5:1. Bicycle movement is not represented in the present version of the model or in the other microscopic models but the models could very well be built out to include them.

The VISSIM model performance was evaluated in two steps. First, the user can check the animation on the screen while the simulation is running to study vehicle movements and interactions with other road users. Second, after completion of the simulation runs, aggregated traffic measurements produced by the model can be studied, e.g. driver behaviour, average travel time, speed, delay and flow.

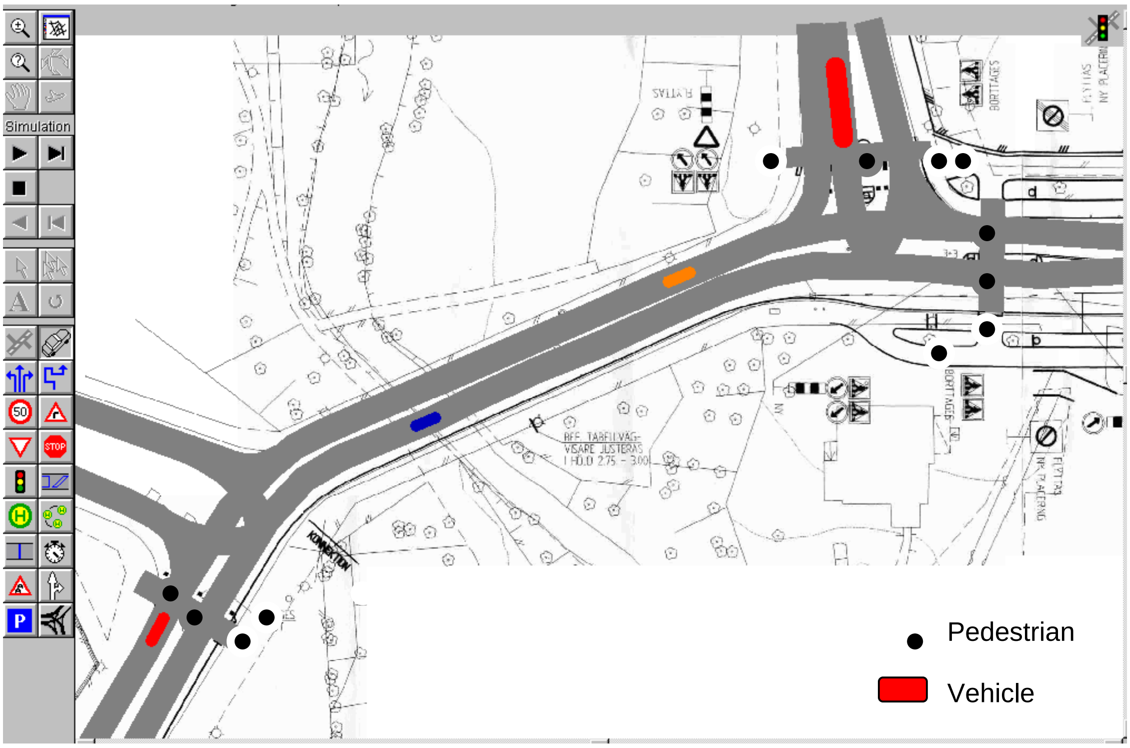


Figure 5:1 Example of microscopic simulation of traffic movement on a main street.

5.1.2 Modelling of the traffic process in an urban street

The analysis of data collection in the field as reported on in chapter 4 had identified a number of side-friction events which influenced speed profiles. Side-friction events with significant impacts on the speed of passing vehicles were

- A crosswalk where a pedestrian approaches to cross
- An occupied bus stop
- A side street were a vehicle is waiting to enter the main street

In the macro study, the following factors were identified as influencing space mean speed on urban streets:

- Vehicle flow
- Flow of crossing pedestrians and bicycles
- Number of lanes
- Bike lane indicator (yes/no)
- Parking indicator (yes/no)

Impacts of side-friction events in the simulation model were programmed based on the observed microscopic behaviour of individual road users, presented in Chapter 4. The speed data of vehicles exposed to these events was used for the coding of the VAP modules. In order to represent a range of traffic conditions, several traffic factors were varied for the production runs of the model. These were:

- Traffic flow on the main street
- Average side street traffic flow
- Frequency of bus service
- Crossing pedestrian flow

In the model calibration process it was ensured that the general behaviour of drivers observed in the real-world scenario was adequately represented in the corresponding microscopic simulation models. Particular attention in this form of simulation modelling was given to aspects related to, amongst other aspects:

- Road-user conformity and giving way out of courtesy
- Desired speed distributions
- Accepted time-gaps in right of way situations
- Car-following behaviour

In addition, behaviour related to the occurrence of studied events was systematically modelled and calibrated.

Similar to the choice of site design for the driver simulator, the selection criteria for the microscopic validation model site were the possibilities to reproduce it from drawings, short-base traffic data and videotapes of traffic movements collected during previous steps of the data collection. Collected traffic data were important inputs to the calibration and validation process. The validation was followed by selection of the experimental study design of the same urban street. It comprised a traffic flow of the street and its side streets, including bus frequency, number of crossing pedestrians, which could be increased or decreased for evaluation purposes.

5.1.3 The simulation model

A simulation model based on an urban street was constructed in the microscopic simulation tool VISSIM. This model was designed to provide a platform for the study of different types and frequencies of particular events. The street selected for modelling was an urban street, resembling the St. Lars Street of the field study (Figure 3:7). The geometric layout, length and traffic conditions of the street were a base for the model construction and validation. The posted speed limit of the street was 50 km/h. The model design consisted of a symmetrical distribution of the intersections, bus stops and pedestrian crossings over the length of the street, with the objectives to facilitate the study effects of different events with a greater degree of isolation. The street in the simulation model had a straight geometric design with two-lane two-way traffic. The intersections had one approach and exit lane on each arm and were regulated by give way signs on the minor streets.

The simulation model is illustrated in Figure 5:2. There were principally three different types of events recorded in the model. Each of the possible events is shown in the figure in accordance with the direction (northbound or southbound):

- Bus stop events – reduced speed when passing a stopped bus on the right-hand side in the direction of travel; braking/stopping for a bus that is pulling out from a bus stop

- Intersection events – reduced speed when passing an intersection side-road approach where there is a waiting vehicle on the right-hand side in the direction of travel; braking/stopping for vehicle that is pulling out from a side-road approach (left and right-hand sides)

- Pedestrian crossing events – reduced speed when passing a pedestrian crossing where there is a waiting pedestrian on the right-hand side in the direction of travel; braking/stopping for pedestrian that is on the pedestrian crossing (left and right-hand sides).

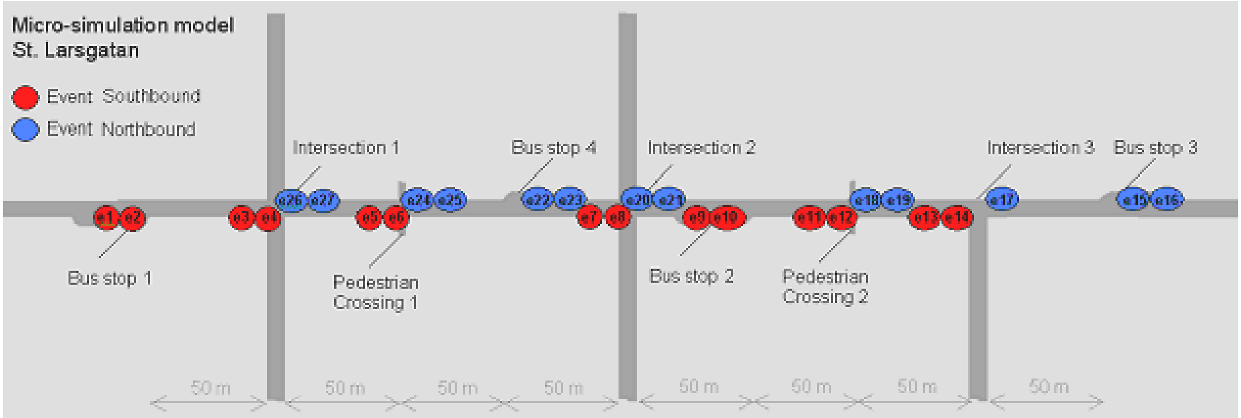


Figure 5:2 Illustration of the microscopic simulation model and event occurrence.

5.1.4 Recording events

Events were recorded using the VAP module that communicates with VISSIM at run-time. The VAP module is intended for the programming of signal logic but can also be used for other logical functions such as those required for the handling of special events. The handling of events is controlled by a series of detectors that can be used to detect vehicle front ends during each update cycle during the simulation. These detectors can also be used to record vehicle speeds. For each of the events described above there is always a detector to determine whether or not there is a bus waiting at a bus stop, a vehicle waiting on an intersection side road, or a pedestrian waiting at a pedestrian crossing. If this is the case, an event is determined to be "active". There are also similar detectors that detect if a bus is pulling out from a bus stop, or if a vehicle is pulling out from an intersection side road, or if there is a pedestrian on a pedestrian crossing.

When an event is active, the speeds of all approaching vehicles that are likely to be affected by the event are recorded on a series of detectors that cover 5-metre intervals from the point where the event originates, and 40-50 metres further upstream. When an event is classed as "active" the desired speed of vehicles is adjusted from a point upstream to a point immediately past the point where the event originated. The actual reduction in speed for each type of event at different distances is calibrated against the existing empirical data.

Even when events are "inactive" the speeds are also recorded at each of the detectors in order to be able to compare the differences between active and inactive events.

During each simulation run the speed values at each detector are averaged over the entire simulation period during all "active" and "inactive" time-periods. A standard deviation was also calculated in conjunction with the mean values. The results from each detector during active and inactive time-periods can then be used to display the main effect of each event.

Figure 5:3 illustrates the placement of detectors for the VAP-logic event handling at bus stops. Similar logic was also used for intersections and pedestrian crossings.

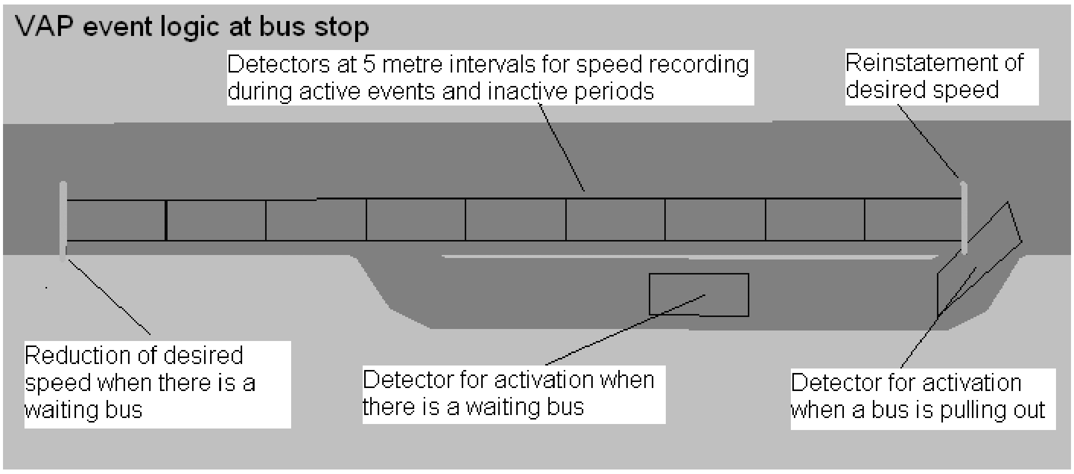


Figure 5:3 VAP-logic event handling at bus stops

5.1.5 Model input

The dynamic model input data was based directly on the empirical field measurements conducted on St. Lars Street. This data included:

- Speed distribution data
- Vehicle headways
- Vehicle traffic flows
- Numbers of pedestrians crossing the street
- Turning movements
- Passengers getting on and off buses
- Bus route frequencies

Data such as speed distribution, vehicle headways and traffic flow was gathered from the short-base measurement for the afternoon hours the same day as the field studies reported in chapter 3. The data on vehicle, bus and pedestrian movements were extracted from the video recordings made during the field day and the afternoon peak hour between 16.00 and 17.00.

5.1.6 Model calibration

A number of traffic behavioural functions in the program were modified, or added, in accordance with the behavioural data collected in the field within the present study. The behaviour modification included:

- Giving way and stopping behaviour of drivers; a ratio of compliant and non-compliant drivers was implemented in the simulation models to correspond to observed behaviour at traffic intersections (giving way out of courtesy), pedestrian crossings (stopping for waiting pedestrians), and bus stops (stopping to allow buses to pull out).

- Speed reduction behaviour of all drivers when passing an unoccupied pedestrian crossing, bus stop or intersection where there are no vehicles waiting on the side adjoining roads.

The output of the model, e.g. speed patterns of the simulated vehicles passing an occupied pedestrian crossing, was checked against speed patterns in the field. The model was modified until the modelled speed behaviour and travel time data was in conformity with field observations.

5.1.7 Model validation

When the model was completed, it was tested and validated to measurements collected in the field. This included ensuring that modelled traffic volumes and turning movements were consistent with the field data at many different points throughout the model.

The case for validation model was tested primarily against travel times collected in the field using the test vehicle during the peak hour (Table 5:1). The distance between the two travel time measurement points was 565 metres. The travel times of undisturbed test vehicle runs, where there was no disruption caused by intersection signals, was used and compared to the travel times generated by the simulation model. The case for validation model was run ten times using different random seed number combinations.

Table 5:1 Comparison of travel time data from field data and microscopic simulation base case for validation.

Measure	Travel time (sec) Direction Southbound	Travel time (sec) Direction Northbound
Average travel time, peak hour field data of the test vehicle in uninterrupted flow	54.6 ± 1.7 SD 5.0	58.0 ± 2.0 SD 6.4
Average travel time, peak hour of the case for validation model	56.7 ± 0.1 SD 1.5	60.1 ± 0.3 SD 3.5

The model estimated the travel times of undisturbed trips well. This is confirmed by comparisons of values. The average travel times calculated by the model were 3.8% greater than the field travel time data (in a range of 0.8 to 7.0%) in the southbound direction, and 3.6% greater than the field data northbound direction (the range was 0.7 to 6.7%). The travel times of the case for validation is within one standard deviation of the actual observed value, which follows established validation guidelines (Choa et al. 2003).

5.1.8 Experimental study design

This study considered various main and side street traffic flows, numbers of crossing pedestrians and bus service frequencies. The base scenario had traffic conditions on the main street similar to the ones used in the validation case, i.e. a traffic flow on the main street of 700 vehicles per hour, bus frequency of 30 buses per hour, and 280 crossing pedestrians per hour and kilometre. Traffic flows on the side streets in the validation case were large and was reduced to a minor figure in the other nine cases. The turning movements at minor intersections used in the nine cases were 5 percent turning into a side street on the right, 5 percent turning into a side street on the left and ninety percent continuing straight ahead. The combination of the variables resulted in nine scenarios (Table 5:2).

Cases 0, 3 and 6 represent the base level of side-friction (1.0) caused by buses stopping at bus stops and pedestrians crossing the street. These figures were increased by 50 percent in Cases 1, 4 and 7 – the cases thereby represent a higher level of side-friction designated 1.5 in this study. In Cases 2, 5 and 8 the frequency of bus service and number of crossing pedestrians was reduced by one half of the original value – representing a side-friction level designated 0.5.

Table 5:2 Street and traffic designs selected for the traffic simulation in micro models.

	Case for validation	Case			Case			Case		
		0 base scenario	1	2	3	4	5	6	7	8
Traffic flow main street (veh/h)	700	700	700	700	1050	1050	1050	350	350	350
Average side street traffic flow (veh/h)	300	67	67	67	100	100	100	33	33	33
Frequency of bus service (buses/h)	30	30	45	15	30	45	15	30	45	15
Crossing pedestrian flow (ped/h, km)	280	280	420	140	280	420	140	280	420	140

5.1.9 Data reduction and analysis

The simulation program was run ten times for each case for 4,500 seconds. Traffic data was recorded during the last 3,600 seconds of each simulation. A total of 90 simulations were performed after the validation process was completed. The initial set of vehicles in each run was randomly decided by random seed number combinations. The traffic movements produced in the simulation runs were collected and reduced into average value and standard deviation of the ten runs of each case. The collected data was

- Travel times and number of through vehicles on the main street
- Speed patterns of vehicles passing the 27 possible events of the studied case.
- Number of occurrences of each event and its location
- Vehicle speed and flow measured at nine points on the main street
- Vehicle flow on each side street and for each direction of travel
- Pedestrian speed and flow at two measurement points on a crosswalk

The average travel speeds of through vehicles on the main street were calculated from distance travelled and average travel times. The speed information was entered into a database (Table 5:3) together with the variables Traffic flow in both directions of travel per hour, Number of crossing pedestrians per hour and kilometre, Number of side streets per kilometre, Flow on side streets per hour and kilometre and Number of buses stopping at stops per hour and kilometre etc. The variables were analysed by multiple regression technique with average travel speed as the dependent variable.

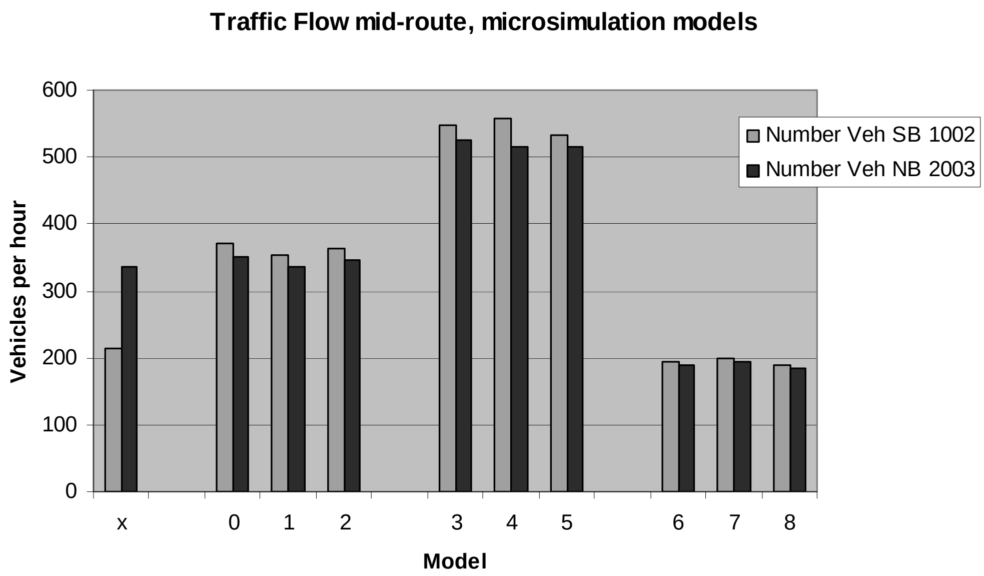
Table 5:3 The database of average travel speeds, resulting from simulation runs, and traffic variables.

Case number and direction, Southbound or Northbound	Average travel speed (km/h)	Two-way traffic flow per hour	Structure of environment	Number of lanes	Lane width (m)	Median indicator	Street function	Bicycle indicator	Bus stop indicator	Parking indicator	Number of side streets per km	Number of crossing pedestrians per hour and km	Traffic flow on side streets per hour and km	Number of buses stopping at bus stops per hour and km	Traffic flow in studied direction per hour	Flow oncoming traffic per hour	Flow through traffic per hour
0 SB	38.3	722	0	1	4.5	0	1	0	1	0	3.5	269	273	106	371	352	316
1 SB	36.6	688	0	1	4.5	0	1	0	1	0	3.5	404	273	159	352	336	301
2 SB	40.4	709	0	1	4.5	0	1	0	1	0	3.5	135	273	53	364	345	311
3 SB	33.0	1072	0	1	4.5	0	1	0	1	0	3.5	269	389	106	547	525	465
4 SB	30.2	1074	0	1	4.5	0	1	0	1	0	3.5	404	389	159	559	516	476
5 SB	35.7	1049	0	1	4.5	0	1	0	1	0	3.5	135	389	53	534	516	452
6 SB	39.2	384	0	1	4.5	0	1	0	1	0	3.5	269	159	106	194	189	164
7 SB	37.2	396	0	1	4.5	0	1	0	1	0	3.5	404	159	159	200	195	171
8 SB	41.6	371	0	1	4.5	0	1	0	1	0	3.5	135	159	53	188	183	158
0 NB	38.2	722	0	1	4.5	0	1	0	1	0	5.3	269	237	106	352	371	311
1 NB	36.6	688	0	1	4.5	0	1	0	1	0	5.3	404	237	159	336	352	297
2 NB	40.3	709	0	1	4.5	0	1	0	1	0	5.3	135	237	53	345	364	305
3 NB	31.0	1072	0	1	4.5	0	1	0	1	0	5.3	269	353	106	525	547	465
4 NB	30.7	1074	0	1	4.5	0	1	0	1	0	5.3	404	353	159	516	559	479
5 NB	33.9	1049	0	1	4.5	0	1	0	1	0	5.3	135	353	53	516	534	457
6 NB	40.1	384	0	1	4.5	0	1	0	1	0	5.3	269	192	106	189	194	166
7 NB	38.0	396	0	1	4.5	0	1	0	1	0	5.3	404	192	159	195	200	172
8 NB	42.2	371	0	1	4.5	0	1	0	1	0	5.3	135	192	53	183	188	160

5.2 RESULTS

5.2.1 Descriptive traffic data

The average number of vehicles and their speed were *inter alia* collected at a mid-route point in the simulation model (Figure 5:4). The number of vehicles corresponded to input two-way flow of 350, 700 or 1050 vehicles per hour. The average speed mid-route was approximately 40 km/h in model cases 0, 1, and 2. Cases 3 to 5 had a 50 percent larger traffic flow and the resulting average mid-route speed was around 35 km/h. Cases 6 to 8 had a traffic flow which was half of the flow in the base scenario. The mid-route speeds of that traffic condition was on average 45 km/h. In the validation case (designated x in the figure), the calculated traffic flow northbound was 50 percent larger than the southbound traffic flow and this was in accordance with observed flow and turning movements.



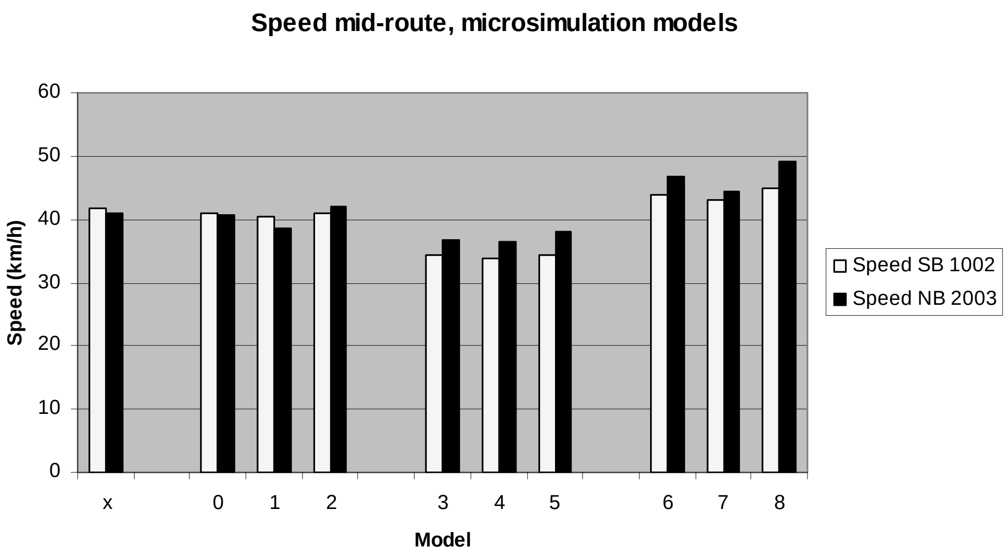
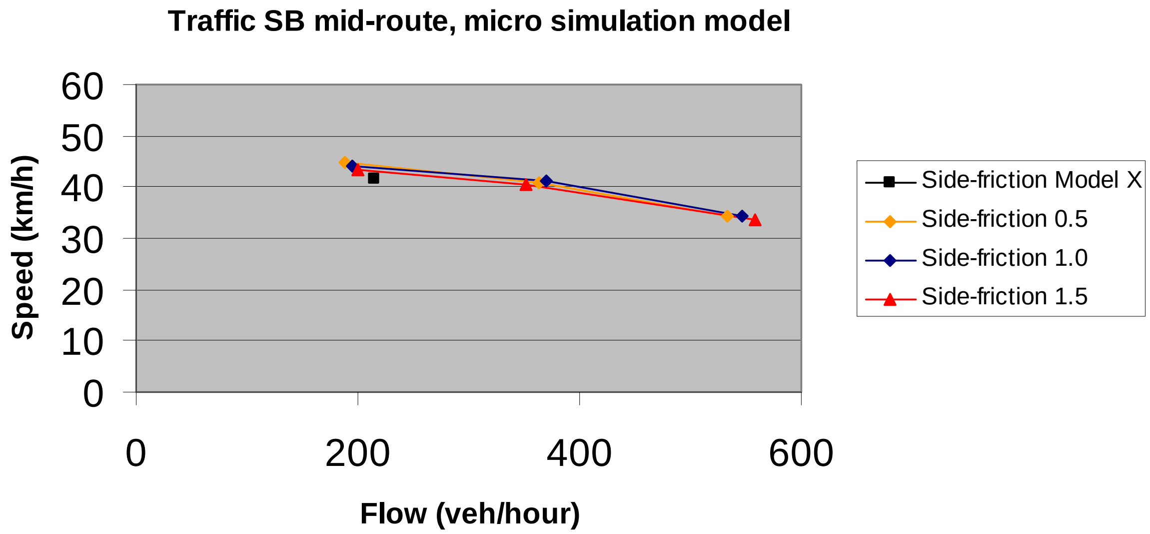


Figure 5:4 Average traffic flow and speed mid-route in the Southbound (SB) and Northbound (NB) directions of travel for the validation case and cases 0 to 8 of the simulation runs.

Vehicle speed and flow measurements for three levels of side-friction frequency (0.5, 1.0 and 1.5) are shown in Figure 5:5. The measurements were made mid-route and for the northbound and southbound direction of travel respectively. The validation case is designated x in the figure. The base scenario and cases 3 and 6 represent the base level of side-friction observed in the field. The frequency of bus service and crossing pedestrian flow was increased by 50 percent in case 1, 4 and 7 and reduced by 50 percent compared to the base level in cases 2, 5 and 8. Vehicles which were exposed to 0.5 level of side-friction drove with a higher speed past the mid-route measurement point in the simulation model than vehicles exposed to the side-friction levels 1.0 and 1.5. This was especially true for northbound travel.



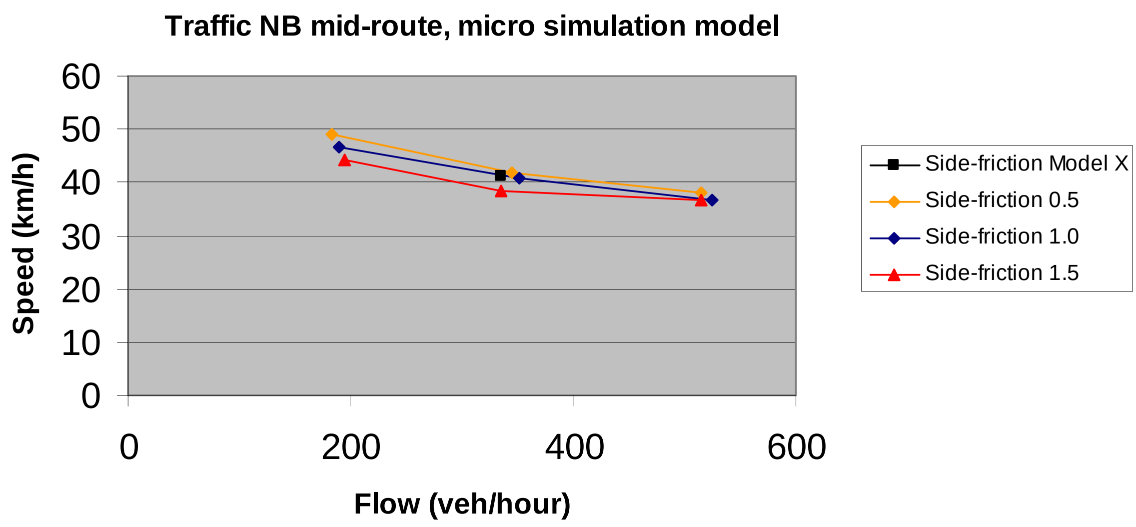


Figure 5:5 *Average speed-flow relationship for three levels of side-friction. Measured mid-route for the Southbound (SB) and Northbound (NB) directions of travel.*

5.2.2 Modelling of average travel speed data

The multiple regression equation of the average travel speeds, resulting from the ninety production runs with the microscopic traffic simulation modelling of an urban street, was as follows:

$$\bar{v}_{sim} = 48.7 - 0.011 \times Flow - 0.015 \times Ped \qquad (5:1)$$

where

$\bar{v}_{sim}$ = average travel speed (km/h), from simulation runs
Flow = traffic flow in both direction of travel per hour
Ped = number of crossing pedestrians per hour and kilometre

The analyses showed a large explanatory power of the factors Traffic flow and Number of crossing pedestrians. The following variables among those listed in table 5:3 proved to be non-significant ($p<0.05$)

- Number of side streets,
- Flow on side streets per hour and kilometre and
- Number of buses stopping at stops per hour and kilometre.

Due to the study's experimental design, the last variable was correlated to the variable Number of crossing pedestrians. The R2 value of the regression of the urban street represented in the simulation model was 0.91 (Table 5:4). The standard error of the estimate was 1.21 and the F value was 74.26. Exclusion of the variable Number of crossing pedestrians led to a 0.20 reduction of the R2 value.

The variable Traffic flow in both directions of travel on the main street ranged from 370 to 1070 per hour. The variable inflicted, in compliance with the equation, an average speed reduction of 4.1 to 11.8 km/h. The speed reduction caused by the variable Number of crossing pedestrians (ranging from 135 to 405 per hour and km) was between 2.0 and 6.1 km/h.

Table 5:4 Output of the multiple regression analysis simulations results for urban streets.

	Unstandardized Coefficients	Standardized Coefficients	t-value	Sig.
	B	Beta		
(Constant)	48.714		46.544	.000
Flow	-.011	-.827	-10.571	.000
Ped	-.015	-.463	-5.914	.000
Model summary		ANOVA		
R^2	Std. Error of the Estimate	F	Sig.	
0.908	1.2090	74.260	0.000	

5.3 DISCUSSION

The applied method of enhancing a microscopic traffic simulation model with side-friction representation proved successful for prediction of impacts on speed by side-friction events caused by other road users. This shows that simulation modelling can be successfully used for urban street speed modelling in the applied context. The same approach should be possible to use for other street designs and side-friction levels, given that careful calibration and validation has been carried out.

5.4 CONCLUSIONS

The microscopic traffic simulation model was calibrated using individual driver behaviour field data, and was shown to reproduce travel times of undisturbed trips within four percent of field travel time data used for validation. Several significant variables influencing urban speed were identified in the analysis of the collected field data and driving simulator study. The significant variables were

- Traffic flow in the studied and oncoming directions of travel;
- Pedestrian and bicycle movement;
- Buses entering and exiting from bus stops; and
- Street type and design.

These traffic behavioural functions were modified and added into the microscopic simulation model prior to the final validation and calibration runs of the urban street model. Results of the multiple regression analysis of the microscopic model showed *Number of crossing pedestrians* to have a significant impact on average travel speed. The variable *Traffic flow* was also significant and had a greater beta value.

6. SYNTHESIS AND CONCLUSIONS

6.1 REVIEW OF THE RESEARCH STRATEGY

The well known problem of how to design streets and their environments to guide road users to drive in accordance with the posted speed limit, with the objective of promoting traffic safety, initiated this study. The research strategy consisted of a bottom-up approach based on empirical data collected at the individual driver behaviour level (micro level) for a variety of street types and urban settings. Throughout the research, a special focus was placed on capturing the influence on driver speed of interactions with pedestrians, cyclists and other road users. A microscopic traffic simulation model was calibrated, validated and used for production runs resulting in detailed speed characteristics for vehicles travelling along the modelled link segment.

The behavioural data for the micro study was collected for ten streets and consisted of speed profiles for routes as well as detailed speed information at specific events. Controlled experiments conducted in a driving simulator produced supplementary information on driver behaviour for specific events occurring on an urban street. Parallel with the micro study, traffic characteristics at the link level were analyzed in a macro study. Speed-flow data variables, combined with street site variables including pedestrian and bicycle movement, were analyzed using multiple regression techniques with speed as the dependent variable.

The data for the macro study was collected at forty measurement points located in six cities and comprised 9,000 five-minute interval observations of space mean speed. Travel time data was collected on nine routes, in both directions of travel, for one off-peak hour and one or two peak hours depending on the site.

Multiple regression analysis using microscopic traffic simulation results for one urban street type was applied in the speed modelling process. Similar analysis was also performed using data from the macro study for three street types. Final speed relationships were obtained based upon a synthesis of developed analysis methods.

6.2 RESULTS

The micro study identified several factors that influenced vehicle speed at a micro level. Significant impact ($p<0.05$) on vehicle speed was reported for the events *pedestrian approaching crosswalk* and *occupied bus stops*. The macro study identified significant impact on speed caused by the variables *street function* and *number of minor intersections per 1 km*. Based on these findings, a microscopic traffic simulation model of an urban street with a posted speed limit of 50 km/h was enhanced and calibrated to represent observed driver behaviour

The speed relationships for the urban street type were calculated from traffic data produced from the microscopic traffic simulation modelling. The analysis, presented in section 5.2.2, showed large explanatory power of the factors *Traffic flow* and *Number of crossing pedestrians.*

The macro study performed for three street types with a posted speed limit of 50 km/h showed several factors that significantly influenced space mean speed. The analyses presented in section 4.2.3 proved that the variables *Flow in the studied direction, Average number of crossing pedestrians and cyclists, Street function* and *Number of lanes in the studied direction* had significant ($p<0.05$) impact on space mean speed.

6.3 COMPARISON WITH EXISTING GUIDELINES

In order to study how the macro models agreed with models of existing guidelines, speed-flow data of arterial, suburban and urban street sites were plotted (Figure 6:1 to 6:3). The figures include speed-flow (V-Q) relationships for cars from the Impact Assessment Catalogue (2001:78) for equivalent street types. The macro model represents space-mean speed and the Impact Assessment Catalogue represents travel speed data. The observed flow in the macro models was recalculated to represent flow per hour and two-way traffic.

The Impact Assessment Catalogue (SRA 2001b) exhibits speed-flow relationships for a range of road types, number of lanes, environments, street functions and vehicle types. For comparison of relationships the following selections were made:

- The SRA multilane roads (4 lanes) in an “outer” of “intermediate” environment were considered to be comparable to the arterial streets model.

- The SRA two-lane roads with an “outer” or “intermediate” environment were considered selected for comparison to suburban street models.

- The SRA two-lane roads with the street function “City” located in a “central” environment were considered comparable to the urban street models.

Figure 6:1 illustrates macro model output of arterial links with two lanes in the studied direction, the street function Thoroughfare or approach (the variable Func = 0), and two levels of the variable Number of intersections per km (the variable Inter= 0 or 3). The plots of speed-flow relationships from the Impact Assessment Catalogue shown in the figure represent 1) arterial links with two lanes in each direction of travel, and 2) Thoroughfare or approach in environment type “outer” or “intermediate” (denoted Y for “outer” and M for “intermediate” in the figure).

The macro model for arterials links with the street function Thoroughfare or approach generally agree with the values modelled in the Impact Assessment Catalogue for the interval of traffic flow 500 – 2,300 vehicles/hour.

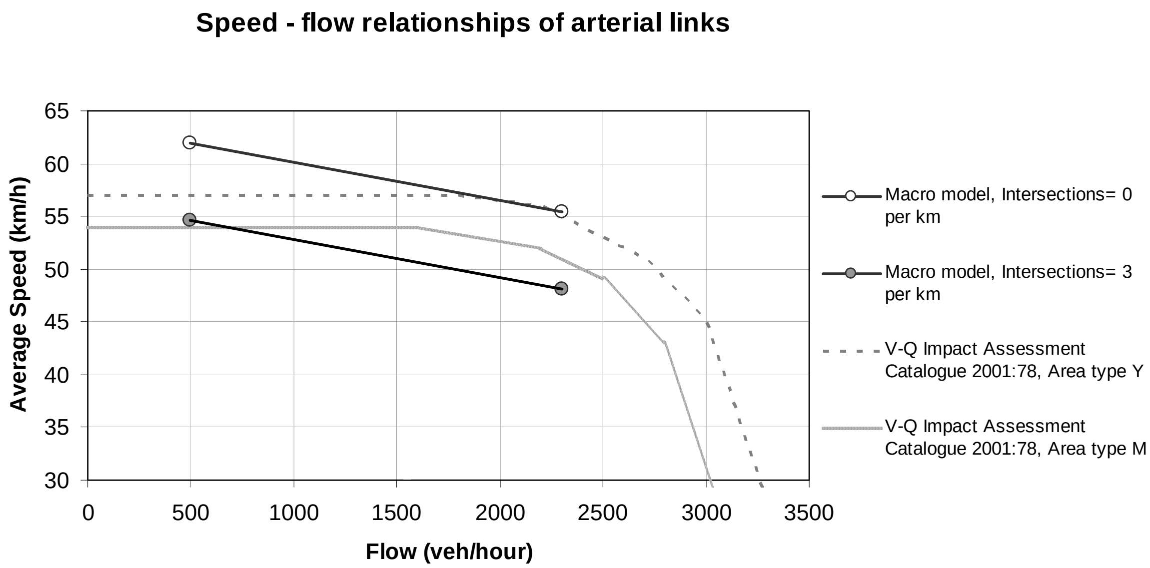


Figure 6:1 Examples of speed–flow relationships for arterial links with the street function of thoroughfare or approach.

Figure 6:2 illustrates macro model output for suburban street links with one lane in the studied direction, street function Thoroughfare or approach (the variable Func set to 0), two levels of Average number of crossing pedestrians and cyclists per hour and km (50 or 150) and two levels of Bus stop indicator (0 or 1). Plots of speed-flow relationships from the Impact Assessment Catalogue are shown in the figure and represent suburban streets with one lane in each direction of travel, street function thoroughfare or approaches in the environment type “outer” or “intermediate”.

The macro study field data of average travel speed for suburban links with a posted speed limit of 50 km/h varied from 40 to 50 km/h. The output of the macro model ranged from 47 to 51 km/h when the traffic flow was 100-1,400 vehicles per hour, Pedestrian flow 150 per hour and kilometre and Bus stop indicator 0, which was close to some of the observed average travel speeds. The calculated speed in the macro models for other combinations of pedestrian flow and bus stop indicator values (Ped=50, Bus=1 and Ped=150, Bus=0) ranged both from 51 to 55 km/h.

The macro models illustrated in the figure generally agree with the speed-flow relationships of the equivalent street type in an outer and intermediate environment presented in the Impact Assessment Catalogue for the interval of traffic flow 100-1,400 vehicles per hour.

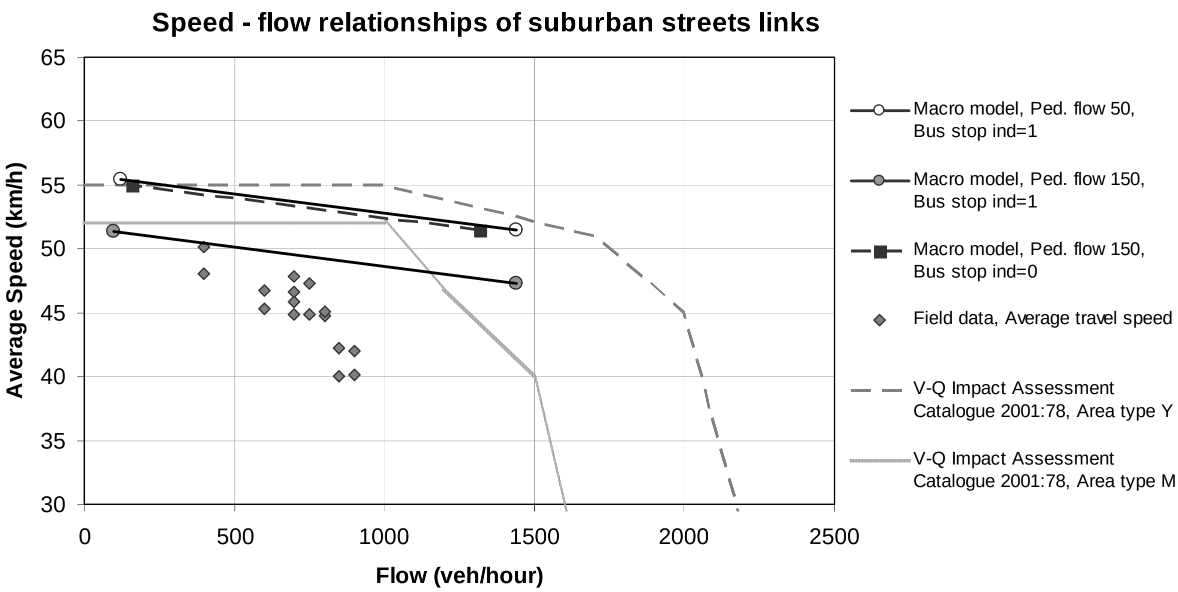


Figure 6:2 Examples of speed–flow relationships for suburban links with the street function of thoroughfare or approach.

The macro models for urban street links are illustrated Figure 6:3. The streets had one lane in the studied direction, street function Other link in the main network (Func=1), two levels of Average number of crossing pedestrians and cyclists per hour and km (150 or 250), no separated bicycle lane on the link (Bic=0) and parking not permitted on the street (Park=0). Plots of speed-flow relationships from the Impact Assessment Catalogue are shown in the figure; representing an urban street with one lane in each direction of travel, and a central environment. The macro study field data of average travel speed for suburban links varied from 27 to 39 km/h.

The output of the macro model ranged from 32 to 40 km/h when the traffic flow variable was 200-1,100 vehicles per hour, a pedestrian flow of 150 per hour and kilometre and bus stop and parking indicator was null. A higher Pedestrian flow of 250 implied speeds ranging from 32 to 37 km/h, for traffic flow up to 800 vehicles per hour, which followed the linear of the observed average travel speeds data and differed by less than one km/h. The results were thus supported by observed average travel speed data.

The plotted speed-flow relationships of the equivalent street type in central area presented in the Impact Assessment Catalogue differ from the macro models for urban street links. The speed difference was over 5 km/h for streets comprising a pedestrian flow of 150, no separated bicycle lane and parking not permitted on the link. Separation of bicycles to a separate lane resulted in a higher speed value from the macro model (4.7 km/h) which implies that the model output was in line with the Impact Assessment Catalogue for the equivalent street type. On the other hand, if parking is permitted on the urban link the output of the macro model is reduced by 5.5 km/h and then again the model differs by over 5 km/h from the speeds presented in the Impact Assessment catalogue for an urban street.

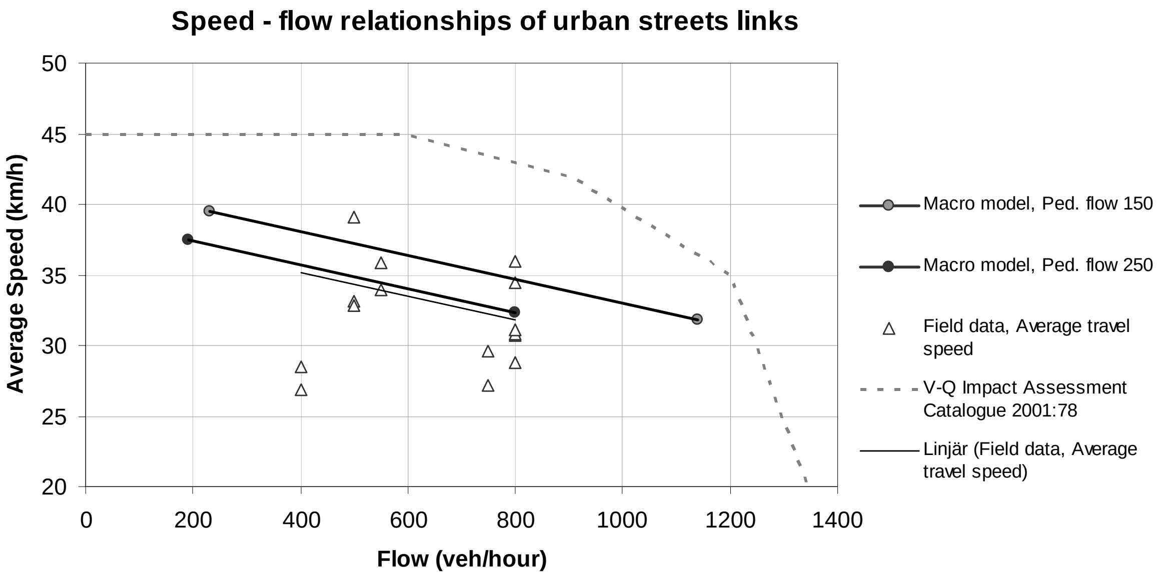


Figure 6:3 Examples of speed–flow relationships for urban links with the street function of other link in the main network.

6.4 DISCUSSION OF THE MICRO AND MACRO STUDY RESULTS

The results of the macro models are similar to Wang and Dixon (2005) proving *Number of lanes in the studied direction* to have the highest influence on speed (excluding traffic flow). The impact of *Number of intersections per km* and *Parking indicator* were also significant in their study.

Results of the micro study for an urban street type were compared with the analysis performed in the macro study. The street used in the comparison had one lane in the studied direction, street function Other link in the main network, no separation of bicycle traffic and parking not permitted on the link. Two way traffic flow used in the microscopic simulation model ranged from 370 to 1,050 vehicles per hour. The micro and macro models for an urban street proved a large degree of explanation from the pedestrian and cyclist flow. The speed reduction measured in kilometres per hour caused by *Average number of crossing pedestrians and cyclist* ranging from 50 to 250 per hour and kilometre were of similar order for both models covered in the study. The speed reduction was 1 to 4 km/h in the micro model, and 1 to 6 km/h in the macro model.

Figure 6:4 shows speed-flow relationships for urban street links based on the micro and macro models for a range of vehicle and pedestrian flow. The speed-flow relationships of the macro model show good agreement with the micro model for traffic flows in the upper range.

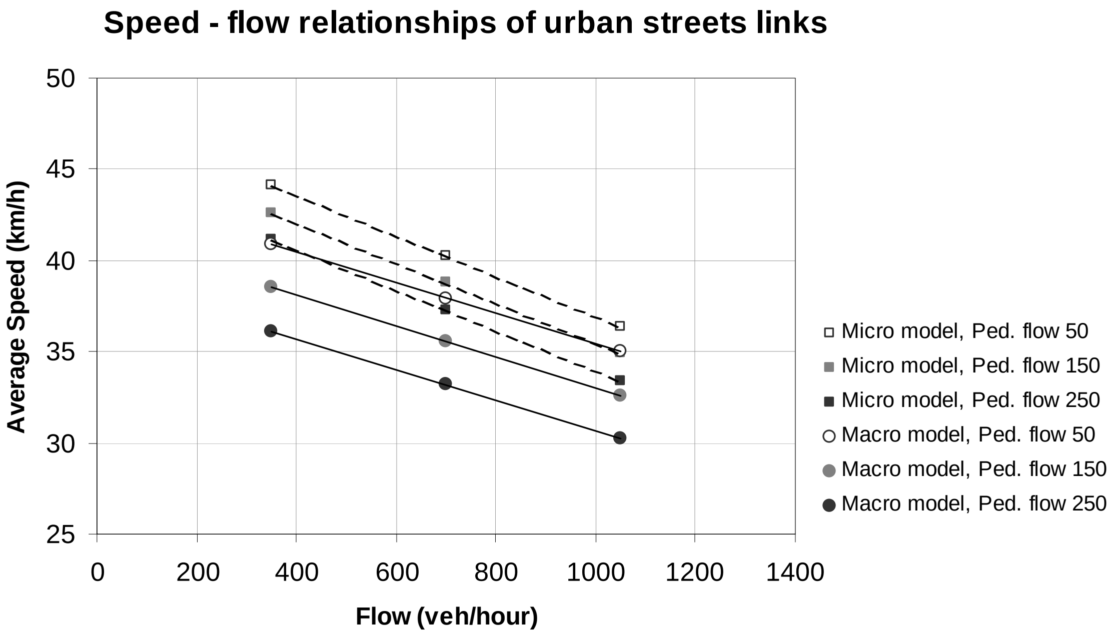


Figure 6:4 Diagram of speed as a function of two-way traffic flow per hour and average number of pedestrian and cyclist flow per hour and kilometre.

6.5 CONCLUSIONS

The research effort presents a methodology for systematic studies of speed characteristics of urban street links. It was pursued from a bottom-up perspective ranging from driver behaviour studies to traffic simulation modelling and included variables not previously addressed in the context of urban speed modelling. The bottom-up approach was successful and provided enhanced knowledge of speed impacts from interaction with a number of side-friction elements. Furthermore, the techniques of driving simulation studies and microscopic traffic simulation, developed in the present study, have a potential to provide systematic knowledge of how urban streets can be designed to improve traffic safety. Application of these techniques provided feedback on how the variables pedestrian and bicycle movements, street factors and traffic flow influence speed on a variety of urban streets with minor intersections. In addition, the computer based microscopic traffic simulation model was successfully used for systematic production runs and provided an alternative to traditional data collection techniques, as well as to evaluate of combinations of street design and traffic conditions.

Finally, a synthesised descriptive model for speed characteristics for arterials, suburban streets and urban streets was generated for traffic flow and street design factors as well as a number of side-friction variables not previously described in the literature. If this model, for instance, is compared with speed-flow relationships presented in the Swedish Impact Assessment Catalogue, a number of interesting conclusions can be drawn. Potentially it would be possible to improve the explanatory power of the relationships in the Catalogue, in particular with respect to side-friction variables, using the results of this study.

6.6 RECOMMENDATIONS FOR FUTURE RESEARCH

In this study an extensive amount of data was collected, analyzed and applied for modelling of speed relationships as a basis for the presented conclusions. Although adequate for the scope and objectives of the study, the methods could be developed further to gain enhanced knowledge of driver behaviour in an urban traffic environment. The following suggestions for future research would facilitate this process.

Data collection methods may be improved and carried out more efficiently, e.g. by using automatic image analysis of video recordings for tracking of vehicles and conflicts with unprotected road users causing side-friction. The traditional speed and flow measurement method (used in the macro study) can, if supplemented with side-friction observations obtained in this way around the observation site, give enhanced input data for the analysis.

The experimental design including the use of a simple driving simulator as a tool to make “controlled experiments” to evaluate drivers’ behaviour when exposed to side-friction events. With a more advanced simulator, other traffic conditions and street designs which were not included could be studied:

- alternative street designs and street environments;
- multiple traffic interactions including dynamic response from the conflicting traffic elements.

The microscopic traffic simulation model, which was enhanced and applied for "controlled experiments" for analysis of speed interactions, can be further developed regarding modelling of the behaviour of unprotected road users. The model can then, after thorough calibration and validation, be applied for the analysis of alternative street designs and street environments including:

- impacts of multiple combinations of side-friction events;
- side-friction events additional to the events represented in the urban street model.

A combination of micro and macro techniques for analysis of speed relationships for urban streets with minor intersections was utilized in the study. Further development of this strategy including methods for synthesis of the results of the "bottom-up" and "top-down" techniques is also needed.

The enhanced "toolbox" for analysis of factors that affect speed choice and speed patterns could be applied for study of other combinations of parameters and contexts:

- urban streets with complex traffic conditions and limited street space;
- rural road designs with a high degree of side-friction or crossing traffic;
- other traffic facilities such as terminal areas.

References

Allen, Rosenthal, Aponso, Parseghian, Cook, and Markham (2000) "A Scenario Definition Language for Developing Driving Simulator Courses".

Amundsen, F H and P Christensen (1986) "Relationship between geometric design and driving speed in residential areas". Oslo: Transportökonomisk Institutt, Norway.

Archer, J (2005) "Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling TRITA-INFRA 05-013" Royal Institute of Technology, Sweden.

Aronsson, K and K L Bang (2005) "Factors Influencing Speed Profiles on Urban Streets" in The Third International Symposium on Highway Geometric Design. Chicago: Transportation Research Board, USA.

Aronsson, K (2006) "Female and male driving behaviour on Swedish urban roads and streets": Swedish Road Administration, Borlänge, Sweden.

Aronsson, K and K L Bang (2007) "Speed characteristics of urban streets based on driver behavior studies and simulation including pedestrian movements" in TRB 2007 Annual Meeting: Transportation Research Board, Washington DC, USA. Accepted for presentation.

Bang, K L, A Carlsson, and Palgunadi (1995) "Development of Speed-flow Relationships for Indonesian Rural Roads using Empirical Data and Simulation." Transportation Research Record 1484, p. 24-32.

Bang, K L (1997) "Indonesian Highway Capacity Manual: Part I, Urban Roads": Directorate General of Highways, Indonesia.

Bang, K L, Z Ronggui, and X Huichen (1998) "Traffic performance and passenger car equivalents for road links and township roads in People's Republic of China." in the Third International Symposium on Highway Capacity, Rysgaard, R (Ed.). Copenhagen, Denmark: Ministry of Transport - Denmark, Road Directorate and Transportation Research Board, USA.

Berge, G and T Vaa (2003) "Feeling of speed: A qualitative study of reasons for speed choices".: Transportökonomisk Institutt, Oslo, Norway.

Bergh, T (1985) "Restidsmätning i tätorter": Vägverket Utvecklingssektionen, Borlänge, Sweden.

Björklund, G (2005) "Driver Interaction; Informal Rules, Irritation and Aggressive Behaviour." Uppsala University, Sweden.

Brandberg, V, R Johansson, and T Gustafsson (1999), Calm Streets!: The Swedish Association of Local Authorities, Sweden.

Brodin, A, A Carlsson, and A Bolling (1982) "The VTI Traffic simulation model" Vol. VTI meddelande 321A: Statens väg- och transportforskningsinstitut, Sweden.

Burghout, W (2004) "Hybrid microscopic-mesoscopic traffic simulation TRITA-INFRA 04-035": Royal Institute of Technology, Stockholm, Sweden.

Carlsson, A and H-Å Cedersund (1998) "A macro speed-flow model for multi-lane roads." in Third International Symposium on Highway, Rysgaard, R (Ed.). Copenhagen, Denmark: Ministry of Transport - Denmark, Road Directorate and Transportation Research Board, USA.

Carlsson, A and M-R Yahya (1998) "Hastighets-flödessamband från VV mätningar 1996" Vol. VTI notat 38: Statens väg- och transportforskningsinstitut, Sweden.

Choa, F, R T Milam, and P E Stanek (2003) "CORSIM, PARAMICS, and VISSIM: What the Manuals Never Told You" in Ninth TRB Conference on the Application of Transportation Planning Methods, Bennett, G a D, R (Ed.): Transportation Research Board, Baton Rouge, Louisiana, USA.

Drottenborg, H (2003) "Are Beautiful traffic environments safer than Ugly traffic environments? Bulletin 211": Lund Institute of Technology. Lund University, Sweden.

Eisele, W L and W E Frawley (2005) "Safety and Operational Analyses of Access Management Treatments: Results of Managing Driveway Density and Installing Raised Medians" in The Third International Symposium on Highway Geometric Design: Transportation Research Board, Chicago, USA.

Elvik, R, A Borger-Mysen, and T Vaa (1997), Trafikksikkerhetshåndbok: Transportekonomisk institutt, Oslo, Norway.

Englund, A, N P Gregersen, C Hyden, P Lövsund, and L Åberg (1998), Trafiksäkerhet: en kunskapsöversikt: Studentlitteratur och KFB, Lund, Sweden.

Ericsson, E (2000) "Urban driving patterns - characterisation, variability and environmental implications. Bulletin 186": Lund Institute of Technology, Lund University, , Sweden.

Fitzpatrick, K, L Elefteriadou, D W Harwood, J M Collins, J McFadden, I B Anderson, R A Krammes, N Irizarry, K D Parma, K M Bauer, and K Pasetti (2000) "Speed prediction for two-lane rural highways" Vol. FHWA-RD-99-171: Texas Transportation Institute, USA.

Fitzpatrick, K and M Wooldridge (2001) "Recent geometric design research for improved safety and operations" in NCHRP Synthesis of Highway Practice 299: Transportation Research Board, Washington DC, USA.

Fitzpatrick, K, P Carlson, M Brewer, M Wooldridge, and S-P Miaou (2003) "Design speed, operating speed, and posted speed practices": Transportation Research Board Washington DC, USA.

Forward, S, I Linderholm, and S Järmark (1998) "Women and Traffic Accidents, Causes, Consequences and Considerations" in the 24th International Congress of Applied Psychology. San Francisco, California, USA.

Gattis, J L and A Watts (1999) "Urban Street Speed Related to Width and Functional Class" Journal of Transportation Engineering, USA 1999/05 125 (3), p. 193-200.

Giese, J L, G A Davis, and R D Sykes (1997) "The Relationship Between Residential Street Design and Pedestrian Safety" in Institute of Transportation Engineers 67th Annual Meeting, USA.

Hakamies-Blomqvist, L, P Henriksson, C Lundberg, and J Östlund (2001) "Strategisk kompensation och körbeteende hos äldre bilförare": Statens väg- och transportforskningsinstitut, Sweden.

Helmers, G, Tornros, J (2004) "Effekt på hastighet och sidoacceleration av läget hos rotationscentrum för snäva kurvors skevning samt inverkan av träning - ett försök i körsimulator.": Statens väg- och transportforskningsinstitut, Sweden.

Hunt, J G (1990) "Pedestrian Safety and Delay at Crossing Facilities in the United Kingdom" Vol. 363A: Statens väg- och transportforskningsinstitut, Sweden.

Johansson, R, L Nilsson, S Wallberg, and M Wärnhjelm (2004) "Trafik för en attraktiv stad: handbok (Eng. *Traffic for an Attractive Town)*": Boverket, Svenska kommunförbundet, Vägverket, Banverket.

Jonsson, T (2001) "Effektmodeller för trafiksäkerhet i tättbebyggt område": LTH, Lund, Sweden.

Jonsson, T (2005) "Predictive models for accidents on urban links. Bulletin 226": Lund University, Lund Institute of Technology, Lund University, Sweden.

Karlgren, J (2001) "Bilars hastighet längs gator med gupp: metod för framställning av hastighetsprofiler och analys av hastighetsförlopp. Rapport 2001:1" Chalmers Tekniska Högskola, Sweden.

Kittelson & Associates, I, T T Institute, and T C Limited (1999) "Transit Capacity and Quality of Service Manual". Washington D.C.: Transit Cooperative Research Program, Transportation Research Board, USA.

Klee, H, C Bauer, E Radwan, and H Al-Deek (1999) "Preliminary validation of driving simulator based on forward speed" Transportation Research Record 1689, p. 33-39.

Linderholm, L (1996a), Åtgärdskatalogen: Svenska Kommunförbundet, Sweden.

Linderholm, L (1996b) "From Rural Road to Urban Arterial Road" Vol. NVF Report 1996:11: Nordiska vägtekniska förbundet, Sweden.

Marler, N, G Harahap, and E Novara (1994) "Speed-flow relationship and side friction on Indonesian urban highways" in The Second International Symposium on Highway

Capacity, Akcelik, R (Ed.) Vol. 2.: Transportation Research Board and Australian Road Research Board, Sydney, Australia.

Merritt, E (2003) "Hierarchical modeling of road traffic networks TRITA-INFRA 03-038" Royal Institute of Technology, Stockholm, Sweden.

NCHRP (1990) "Effective Utilization of Street Width on Urban Arterials" Vol. Report 330. Washington D.C.: Transportation Research Board, National Research Council, USA.

Nilsson, A (2001) "Speed and Time Gaps, 2000. Final Report. Document designation 2001:17": Vägverket Konsult, Borlänge, Sweden.

Nilsson, A (2003) "Utvärdering av cykelfälts effekter på cyklisters säkerhet och cykelns konkurrenskraft mot bil. Bulletin 217": Lund Institute of Technology, Lund University, Sweden.

Nordqvist, S and S O Gunnarsson (1968) "The SCAFT Guidelines 1968: Principles for Urban Planning with Respect to Road Safety" Vol. 5: Statens Planverk, Sweden.

Nordström, A (2006) "Hastighets-flödessamband för gator i tätortsmiljö" Kungliga Tekniska Högskolan, Sweden.

Nyberg, A, J Thiseus, A Englund, and H-E Pettersson (1998) "Informella trafikzoner" Vol. VTI rapport 433: Statens väg- och transportforskningsinstitut, Sweden.

Pettersson, H-E, L Harms, and G Helmers (1992) "Trafikbeteende och vägmiljöegenskaper" Vol. 370: Statens väg- och transportforskningsinstitut, Sweden.

Poe, C M, J P Tarris, and J M Mason, Jr. (1996) "Relationship of Operating Speeds to Roadway Geometric Design Speeds" Vol. FWHA-RD-96-024: Federal Highway Administration, USA.

Poe, C M, J P Tarris, and J M Mason, Jr. (1998) "Operating Speed Approach to Geometric Design of Low-Speed Urban Streets" in International Symposium on Highway Geometric Design Practices: Transportation Research Board, Washington DC, USA.

Polk, M (2005) "Women's and men's valuations of road system infrastructure in Sweden": Swedish Road Administration, Borlänge, Sweden.

PTV (2005) "VISSIM User Manual 4.10". Karlsruhe: PTV AG.

Rezaie, H (2002) "Framkomlighets- och miljöeffekter av vägkuddar: Försök på huvudgator i tätort. Bulletin 205" Tekniska högskolan i Lund, Sweden.

Royal, D (2004) "National Survey of Speeding and Unsafe Driving, Attitudes and Behavior: 2002 Volume II: Findings": National Highway Traffic Safety Administration, Washington DC, USA.

Sakshaug, K (1986) "Fartsgrenseundersökelsen 1985: Fartgrenseendringers effekt på fart og ulykker" Vol. STF63 A86012: Norges Tekniske Högskole. SINTEF. Avd 63, Trondheim, Norway.

Singh, S (2003) "Driver Attributes and Rear-end Crash Involvement Propensity": National Center for Statistics and Analysis, National Highway Traffic Safety Administration, Washington DC, USA.

Smidfelt-Rosqvist, L (2003) "On the relations between Driving Patterns, Exhaust Emissions and Network Characteristics in Urban Driving. Bulletin 213": Lund Institute of Technology, Lund University, Sweden.

Smoker, M D, J P Tarris, and J M Mason (1996) "Relationship between Zonal Variables and Individual Vehicle Speeds on Low-Speed Urban Streets" in 66th ITE Annual Meeting: Institute of Transportation Engineers, Washington DC, USA.

Spolander, K, H Laurell, G Nilsson, and H-E Pettersson (1979) "Bilförares hastighetsanpassning: Underlag och riktlinjer för informationskampanjer i syfte att förbättra bilförarnas hastighetsanpassning." Vol. VTI meddelande 151: Statens väg- och transportforskningsinstitut, Sweden.

St.Jacques, K and H S Levinson (1997) "Operational Analysis of Bus Lanes on Arterials" Vol. Report 26. Washington D.C.: Transit Cooperative Research Program, USA.

Stenbäck, I (2000) "Undersökning av accelerationer och retardationer 1999: resultat- och metodrapport. Publikation 2000:19": Vägverket, Borlänge, Sweden.

Stutts, J, E Rodgman, D Reinfurt, and L Staplin (2001) "The Role of Driver Distraction in Traffic Crashes": AAA Foundation for Traffic Safety, Washington DC, USA.

Stutts, J, J Feaganes, E Rodgman, C Hamlett, T Meadows, D Reinfurt, K Gish, M Mercadante, and L Staplin (2003) "Distractions in everyday driving": AAA Foundation for Traffic Safety, Washington DC, USA.

Swedish Road Administration (1999) "Vägutformning 1994:052": Trafikkontoret för vägutformning, Borlänge, Sweden.

Swedish Road Administration (2001a) "Effektsamband 2000 (Eng. *Impact Assessment Catalogue 2000*)". Borlänge, Sweden.

Swedish Road Administration (2001b) "Effektsamband 2001:78, Nybyggnad och förbättringar (Eng. *Impact Assessment Catalogue 2001:78 Part Construction and Improvement*)". Borlänge, Sweden.

Swedish Road Administration (2004) "Vägar och gators utformning. Pärm 1-4 (Eng. *Road and Street Design. Part 1-4*)". Borlänge, Sweden.

Tarris, J P, C M Poe, J M Mason, Jr., and K G Goulias (1996) "Predicting Operating Speeds on Low-Speed Urban Streets: Regression and Panel Analysis Approaches" Transportation Research Record 1523, p. 46-54.

Thulin, H and A Obrenovic (2001) "Lagen om väjningsplikt mot gående på obevakat övergångsställe" in effekt på framkomlighet och beteende Vol. VTI rapport 468: Statens väg- och transportforskningsinstitut, Sweden.

Towliat, M (2001) "Effects of Safety Measures for Pedestrians and Cyclists at Crossing Facilities on Arterial Roads. Bulletin 195": Lund Institute of Technology, Lund University, Sweden.

Transportation Research Board (2000), Highway Capacity Manual 2000. Washington D.C.: Transportation Research Board, USA.

Turner, S M, W L Eisele, R J Benz, and D J Holdener (1998), Travel Time Data Collection Handbook: Office of Highway, FWHA and Texas Transportation Institute, Texas A&M University Systems; USA.

Wang, J, K Dixon, H Li, and M Hunter (2006) "Operating Speed Model for Low Speed Urban Tangent Streets Based on In-vehicle GPS Data" in TRB 2006 Annual Meeting: Transportation Research Board, Washington DC, USA.

Wardrop, J G (1952) "Some Theoretical Aspects of Road Traffic Research" Proceedings of the Institution of Civil Engineers, Part II, p. 325-362.

Várhelyi, A (1996) "Dynamic speed adaptation based on information technology, a theoretical background. Bulletin 142": Lund Institute of Technology, Lund University, Sweden.

Várhelyi, Hjälmdahl, Hydén, and Draskóczy (2004) "Effects of an active accelerator pedal on driver behaviour and traffic safety after long-term use in urban areas" Accident Analysis and Prevention 36 (2004), p. 729-737.