ABSTRACT

Speed profiles for motor vehicles on urban streets are influenced not only by the street design and traffic performance, events such as interactions with pedestrians and cyclists, buses, on-street parking, exits from minor roads etc. (called “side-friction events”) also affect driver behaviour. A bottom-up research methodology was developed and applied including a wide range of stationary and mobile field surveys for study of individual driver behaviour. Controlled experiments in a driver simulator programmed to represent the studied field sites were also carried out. Speed profiles showed good resemblance between simulated and observed behaviour for the event pedestrian approaches a crosswalk. Simulated speed behaviour of drivers passing an occupied bus stop proved that women drove with a lower speed than men did. All in all, the results showed that crossing pedestrians, occupied roadside bus stops and encounters with vehicles in the opposing direction of travel had a significant impact on driver speed choices.

In a second stage of the project, the observed driver behaviour including response to the studied side-friction events was used for programming of a microscopic simulation model, which was calibrated to represent speed profile changes caused by interaction with other roads users and events as described above. The model was then applied for production of speed patterns and speed flow relationships for a range off different street designs, traffic environments and traffic flow. The resulting models were aimed for use in guidelines to assist planners and traffic engineers in the selection and evaluation of alternative street designs and traffic management measures.
1. INTRODUCTION

1.1 Background

Predictive models for operating speed have been developed for rural roads (Fitzpatrick et al. 2000; Poe et al. 1996), but are less well developed in an 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 movements. The recently developed Planning Guidelines (Johansson et al. 2004) and the Road and Street Design Handbook (Swedish Road Administration 2004) in Sweden present the concept of street environment description and the necessity to incorporate it in the design process. The planning guidelines define 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 (in-street parking, light poles, separation of traffic etc.)

Knowledge of how the street network and streets should be designed to promote road safety has grown in Sweden over a long period time, and has also been implemented in the Swedish Impact Assessment Catalogue (Swedish Road Administration 2001). However, methods for cost efficiency and safety analysis of an investment in urban streets have not yet been outlined. Previous studies (Aronsson and Bang 2005; Bang et al. 1995) have identified quantitative measures regarding relationships between speed, street design and interaction with pedestrians and bicyclists, buses stopping at stops, vehicles parking in or leaving on-street parking places, but they have not been included in the design guidelines. For instance, the posted speed limit of 50 km/h on roads in urban areas was exceeded in average by 3 km/h for all driven kilometres, proven by a national survey (Nilsson 2001). Therefore, there is a need for prediction models of driver speed on urban streets, to be used in guidelines for design of urban streets to operate at the assigned speed.

1.2 Scope and Objectives

Motor vehicle speeds on urban streets are influenced by a large number of factors including geometric design, the surrounding land use, traffic flow, and degree of conflict with pedestrians, cyclists, buses, on-street parking, exits from roadside premises and individual driver behaviour. This paper 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 main aim of the study was to develop aggregated speed prediction models for urban conditions.

The studied urban street segment types were arterials, suburban streets and urban streets with one or two lanes in each direction of travel. The arterials have medians and separated pedestrian and bicycle facilities, and the street links comprise motorised and non-motorised traffic. The studied urban street...
segments include minor intersections where traffic on the studied streets have
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 traffic flow and degree of saturation was
fairly low on most of the studied sites with subsequent high rate of free-flowing
vehicles.

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

2. OVERVIEW OF RESEARCH STRATEGY
The objectives of the study were realized by applying two modes of
investigation:
   a) Micro study of individual driver speed behaviour.
   b) Macro study of behaviour of a driver population.

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 to produce speed – flow relationships for a variety of
urban conditions. The macro study investigated speed behaviour of a
population of drivers by link level. Speed and flow data, combined with street
site variables, were analysed using multiple regression techniques with speed
as the dependent variable. Finally, a synthesis of speed prediction models
was performed based on the micro and macro studies.

3. DATA COLLECTION METHODOLOGY

3.1 Street selection
The research focused on main streets divided into three main types of
facilities; arterials, suburban and urban streets links (Figures 1 and 2). Besides the coverage of a range of cross sections, traffic flow, street functions
and surrounding street environments, the degree of exposure to so called side
friction factors was sought after in the final site selection. The side friction
factors were defined as the impact on traffic performance from interaction with
pedestrians and bicyclists crossing or walking along the street, buses stopping
at stops, vehicles parking in or leaving on-street parking places and vehicles
entering and exiting side streets (Aronsson and Bang 2005; Bang et al. 1995).

Street segments of each type were selected in six cities: Stockholm
(population: 1.8 million); Uppsala (0.2 million); Linkoping (0.15 million);
Vasteras (0.1 million) and Nykoping (0.05 million). At ten of these sites,
combined stationary and mobile data field data collection was performed as
described below. An additional thirty sites included in the short-base speed
and flow surveys by the Swedish Road Administration (SRA) were selected
for the purpose of the study. The SRA performed a random pick of sites in
their traffic measurement program. The data were mostly collected for one
direction of travel. An inventory of site conditions was conducted for all selected sites including all factors that could have an impact on driver speed choice while navigating the segment as well as the connecting links. Survey results of spot speed and pedestrian and bicycle movements on some of the selected sites from a parallel project (Jonsson 2005) were also included in this inventory. The average daily traffic flow on the selected streets ranged from 5 000 to 20 000 vehicles.

3.2 Data Collection Methods Selection

The chief objective for selecting methods for data collection was the ability to capture the influence of side friction variables on driver speed. Two modes of investigation were applied: micro and macro study.

Micro study
The research strategy of the micro study was to collect
a) data on individual driver behaviour 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 of the micro study was to enhance a microscopic traffic simulation model with the collected behavioural data, run it for a range of traffic flows and pedestrian movements, and collect speed–flow relationships and average travel speed data. Details on the microscopic simulation are provided in Section 5 of this paper.

The speed profile data were collected using three methods specifically developed for the purpose of the study as described below.

**Mobile data collection** was carried out with a specially equipped passenger car. The vehicle equipment had the following data collection capability: Automatic logging of time and distance travelled at frequent intervals (0.2 sec), video camcorders mounted inside the vehicle with forward and backward views and storage of the video recording in a digital VCR synchronized with the logging equipment. The test car was operated with six drivers who were instructed to drive with the average speed of traffic (implying they should overtake as many vehicles as they were overtaken by). 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** was applied to obtain full coverage of traffic conditions, side friction events and resulting driving behaviour for a street segment. The data collection was performed using video recordings from a video tower equipped with two remote controlled digital video cameras. This tower could cover a street segment of around 300 m. Semi-automatic video analysis was used to track the movements of all motor vehicles and pedestrians with the purpose to obtain driver behaviour data for speed profile and speed impacts of side friction events.

**Driving simulator studies** were performed to augment the set of field speed data. In laboratory conditions, drivers encountered numerous sets of events when driving a street modelled after one of the actual streets surveyed in the mobile study. The experiments were conducted in a laboratory room with a mock-up car and wall projection of the simulated drive. Thirty-nine licensed drivers (21 male, 18 female, age 22-65) with varying driving experience performed the driving task in the simulator prepared with seven scenarios. Each subject encountered the same fixed sequence of scenarios including routes with a varying frequency of oncoming traffic, traffic on side streets, pedestrians and buses at bus stops. Subjects were mainly recruited from university faculty and staff not otherwise engaged in the project. Participation was rewarded with a cinema voucher.
The field data collection was carried out between June 2002 and May 2003, for one day per site during daylight hours and dry weather conditions. The driving simulator experiments were conducted in October 2004.

**Macro study**

The research strategy of the macro study was to collect at selected street segments including minor intersections aggregated speed data, vehicle flow data, street design and environment variables and frequency of side-friction events. The selected method for this objective was data collection in the field including side friction event impact on driver speed. The collected data consisted of

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

The traffic data including flow, directional distribution and rate of through traffic was collected in short- and long-base stations located at the entry and exit sections of each studied street segment, which were equipped with double pneumatic tubes (National standard for traffic counting) plus video camcorders for data collection. These data were processed to obtain traffic flow, speed, and time headway distribution. Also, vehicle identity was obtained through license plate number registration from manual collection backed-up with video recording. 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 in the form of average travel speed and ratio of through traffic.

### 3.3 Data Analysis Methodology

**Analysis of data collected in the micro study**

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 were 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 were analyzed in detail using the following procedure:

1. Determination of vehicle speed before being exposed to the event (normally determined as speed at arrival of a specified distance from the event location).
2. Tracking of vehicle speed change 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.

**Analysis of data collected in the macro study**
The field data from each short base site was entered into a database with site characteristics and 5-minute observations of traffic flow and average spot speed. The short-base site data were used for multiple regression analysis for each street type separately and all types combined with speed as the dependent variable.

### 4. SUMMARY OF DATA COLLECTION OF SPEED PROFILES

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

Speed profiles of observed vehicles upstream of a crosswalk, when pedestrians approach to cross, from the field study are illustrated in Figure 3. Drivers in Sweden are by law forced to give way to pedestrians at an uncontrolled pedestrian crossing. Initial vehicle speeds ranged from 30 to 50 km/h on the observed street. The speed dropped approximately 45 meters prior to the cross walk if a pedestrian approached to cross. The observed vehicle speeds reduced to a range of 20 km/h or less, which permitted the pedestrians to cross. The vehicles stopped in average 5 meters ahead of the crosswalk marking in the street.

Driver speed profiles prior to a crosswalk collected in the simulator study are illustrated in Figure 4. Initial vehicle speeds approaching a crosswalk in the simulator ranged from 25 to 50 km/h. The speed dropped approximately 60 meters prior to the cross walk if a pedestrian approached to cross. The vehicle speeds reduced to the range of 30 km/h or less if the pedestrian was given right of way. The vehicles stopped in average 20 meters ahead of the crosswalk in the driving simulator. Several of the subjects expressed difficulties when estimated distance while driving in the simulator and therefore stopped earlier than in reality.

The collected speed profiles showed firstly good resemblance between simulated and observed behaviour for the event of a pedestrian approach a crosswalk, and secondly a great likeness of male and female speed behaviour.
FIGURE 3  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  Speed profiles of observed vehicles upstream of a crosswalk on an urban street, when pedestrians approach to cross, collected in driving simulator studies.
Male driver speed past an occupied bus stop
driving simulator study

Female driver speed past an occupied bus stop
driving simulator study

FIGURE 5 Speed profiles of male and female drivers respectively at an occupied bus stop. Collected in the driving simulator study.

Speed profiles of drivers passing an occupied bus stop were collected in the driving simulator study. Figure 5 illustrates the speed profiles of the male and female drivers respectively at this event. The lane width of the street in this scenario was 3.5 meters. The buses at the bus stop stood on a distance of 3.9 and 4.1 meters from the centre line in the experiment and in accordance with measures of bus location of the field study. The driven speed past the bus stop area was notably higher for male drivers than female.
5. MICROSCOPIC TRAFFIC SIMULATION

5.1 General
A microscopic simulation model was enhanced and calibrated to represent the observed driver behaviour on an urban street (Figure 6). The model (VISSIM) was used to produce speed patterns and speed flow relationships for the studied range of traffic conditions. Principally, three different types of events were recorded in the model.

- **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 6 Illustration of the microscopic simulation model and event occurrence.](image)

5.2 Recording Events
Events were recorded using the VAP (Vehicle Actuated Programming) module, intended for the programming of signal logic, which communicates with VISSIM at runtime. The handling of events was controlled by a series of detectors used for detection of vehicle fronts during each update cycle during the simulation. These detectors were also used for recording of vehicle speeds. For each of the events described above there was a detector to determine whether or not there was a bus waiting at a bus stop, a vehicle waiting on an intersection side road, or a pedestrian waiting at a pedestrian crossing.
5.3 Model Calibration
A number of traffic behavioural functions in the program were modified, or added, in accordance to the behavioural data collected in the field and in the driving simulator within the present study. The modified behaviour included:

- Yielding and stopping behaviour of drivers; a ratio of obedient and non-obedient drivers was implemented in the simulation models to correspond to observed behaviour at traffic intersections (courtesy yielding), 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.

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

The base model used for validation was tested primarily against travel times collected in the field using the test vehicle during the peak hour. The travel times of undisturbed test vehicle runs were used and compared to the travel times generated by the simulation model. The base model was run ten times using different random seed number combinations. The model estimated the travel times of undisturbed trips satisfactorily; the average travel times calculated by the model were 3.6% greater than the field travel time data.

5.5 Experimental Study Design
This study considered various main and side street traffic flows, numbers of crossing pedestrians and bus service frequencies. The combination of the variables resulted in nine scenarios (Table 1).

<table>
<thead>
<tr>
<th>Case for validation</th>
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<td>Traffic flow main street (veh/h)</td>
<td>700</td>
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<td>700</td>
<td>1050</td>
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<tr>
<td>Average side street traffic flow (veh/h)</td>
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<td>67</td>
<td>67</td>
<td>100</td>
</tr>
<tr>
<td>Frequency of bus service (buses/h)</td>
<td>30</td>
<td>30</td>
<td>45</td>
<td>15</td>
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</table>
5.6 Analysis and Results

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

\[ V_{\text{sim}} = 48.7 - 0.011 \times \text{Flow} - 0.015 \times \text{Ped} \]  

Where

- \( V_{\text{sim}} \) = average travel speed (km/h), from simulation runs
- \( \text{Flow} \) = traffic flow in both direction of travel per hour
- \( \text{Ped} \) = number of crossing pedestrians per hour and kilometer

The analyses showed a large explanatory power of the factors Traffic flow and Number of crossing pedestrians. Analyzed variables that resulting in being non significant (t < 0.05) when the independent variables listed above were investigated were the Number of side streets, Flow on side streets per hour and kilometre and Number of buses stopping at stops per hour and kilometre. The latter variable was, due to the study experimental design, 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. Exclusion of the variable Number of crossing pedestrians led to a 0.20 reduction of the R2 value.

The results of the multiple regression analysis of average travel speed data from the micro study of an urban street were compared to the analysis performed on average spot speed (macro model) for the same street type. Both analyses proved a large degree of explanation from the factor Pedestrian and bicycle movements. The speed reduction measured in kilometres per hour caused by crossing pedestrians and bicyclists ranging from 50 to 250 per hour and kilometre, were of similar order for both models covered in the study. In the micro model, the speed reduction was 1 to 4 km/h. The range of speed reduction caused by the variable calculated in the macro model was 1 to 6 km/h, in the urban street model.

CONCLUSION

Speed characteristics of urban streets were investigated in the study. The influence of traffic flow and interaction with other road users were a primary focus, and methods of investigating this influence were developed. Vehicle speed profiles were collected from field and driving simulator studies for a range of street types and traffic flow conditions. Several significant variables influencing urban speed were identified in the analysis of the collected data. 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 proved the variables Traffic flow and Pedestrian movements to have a significant impact on average travel speed.

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