

TRANSFERABILITY OF URBAN MICRO-SIMULATION METHODS

Ken Fox

Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT, UK
Tel: +44-113-233-5351, Fax: +44-113-233-5334, E-Mail: K.A.Fox@leeds.ac.uk

Abstract

Transferability is a key issue in the global environment that transport modellers often find themselves working in today. If a model has been developed using data at one location, can this help with the analysis at another site? This paper addresses this transferability problem for urban micro-simulation models. It reports on work carried out in the SMARTTEST project that has been part funded by the European Commission DGVII.

Three micro-simulation tools have been used in the study, namely:

- DRACULA - developed by ITS, Leeds,
- NEMIS - developed by Mizar Automazione, Turin and
- AIMSUN2 - developed by UPC, Barcelona.

All three tools were used to model a road network in Leeds. Comparisons were made between the outputs of each of the tools and data collected from the real road network.

Other issues addressed include:

- the ability of each of the tools to model all the features found in the test network,
- whether default values for calibration parameters such as those for car following are valid at the test site and
- the sensitivity and robustness of the results.

INTRODUCTION

The Transport Directorate (DGVII) of the European Commission is part funding the SMARTTEST project which is aiming to improve road traffic micro-simulation models. One of the issues being tackled in this project is transferability. In the context of road traffic micro-simulation models, transferability analysis needs to answer the following two key questions:

1. If we have a model developed using data at one site in Europe, can this help with the analysis at another site elsewhere in Europe?
2. How confident can we be that any conclusions we draw at one site, after evaluating a scheme with a micro-simulation model, are valid at another site?

This paper covers work done in the SMARTTEST project to answer these questions. The project has done this by attempting to model a small test network in Leeds with three different micro-simulation packages developed by partners within the SMARTTEST project consortium. The paper starts with a description of each of the micro-simulation models. It then goes on to describe the test network and the data

collected from the street for comparison with the model outputs. Next, the different modelling approaches used by each of the micro-simulation models are examined and compared. The assumptions made in order to use each model to simulate the test network are detailed.

THE MICRO-SIMULATION MODELS

The SMARTEST project consortium consists of eight partners from four European countries. Four different micro-simulation models are being enhanced by the project, three of which have been used in this study. These are AIMSUN2, DRACULA and NEMIS. Each model has been developed in a different European country; AIMSUN2 in Spain, DRACULA in the UK and NEMIS in Italy.

AIMSUN2

AIMSUN2 (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks) has been developed by the Universitat Politècnica de Catalunya (Ferrer and Barcelo, 1992). It is a software tool capable of modelling real traffic conditions in an urban network which may contain both expressways and arterial routes. AIMSUN2 is a combined discrete-continuous simulator: there are some elements of the transportation system (vehicles, detectors) whose state changes continuously over the simulated time period, while there are other elements (traffic lights, entrance points) whose state changes discretely at specific points during the simulation time. It provides very detailed modelling of the traffic network: it distinguishes between different types of vehicles and drivers; it can deal with a wide range of network geometries; it can also model incidents, conflicting manoeuvres, etc.

AIMSUN2 needs three types of input data: the network description, the traffic signal control plans and the traffic conditions. The network description contains information about the geometry of the network, turning movements, layout of links (or sections) and junctions and location of detectors. The traffic control plans define the signal stages and their durations for signal controlled junctions and the priority definition for unsignalized junctions. Two options are available to define the traffic flows in the network. Either the traffic flows for the input links and the turning proportions at junctions or an O/D matrix can be used..

The outputs provided by AIMSUN2 include a continuously animated graphical representation of the traffic network, a printout of statistical data (flows, speeds, journey times, delays, stops), and data gathered by the simulated detectors (counts, occupancy, speeds, queue lengths).

DRACULA

DRACULA (Dynamic Route Assignment Combining User Learning and Micro-simulation) is a microscopic traffic network modelling suite, conceived and developed at the Institute for Transport Studies, University of Leeds over a five year period (Liu et.al., 1995). The development, testing and validation of the model have been primarily funded by a large grant from the UK Engineering and Physical Sciences Research Council, although some early applications of the model were possible under funding from the EC's DRIVE II Telematics programme. Applications of this model in progress, or to commence shortly, include the study of congestion based road pricing, real time traffic signal control, dynamic route guidance, segregated busway design,

emergency evacuation procedures (eg. Following chemical explosions, floods), and strategic (inter-urban) modelling.

NEMIS

NEMIS is a scientific software package developed by Mizar Automazione in Turin, Italy (Mauro, 1991). Since its creation, it has been used principally for research and development work and for the technical assessment of traffic control strategies. It has been developed for the micro-simulation of urban traffic (private and public) in large scale networks. It is capable of modelling urban networks and vehicle behaviour in considerable detail, and is well structured to meet a variety of application needs. Its usefulness has been demonstrated for the following tasks:

- analysis of the effects of regulation and network modification on traffic mobility
- evaluation of different traffic signal control strategies
- testing of traffic assignment techniques
- simulation and evaluation of route guidance strategies and variable message systems

Simulation occurs in increments of one second. Outputs include pollution emissions and fuel consumed by vehicles in the network.

THE TEST NETWORK

Network Description

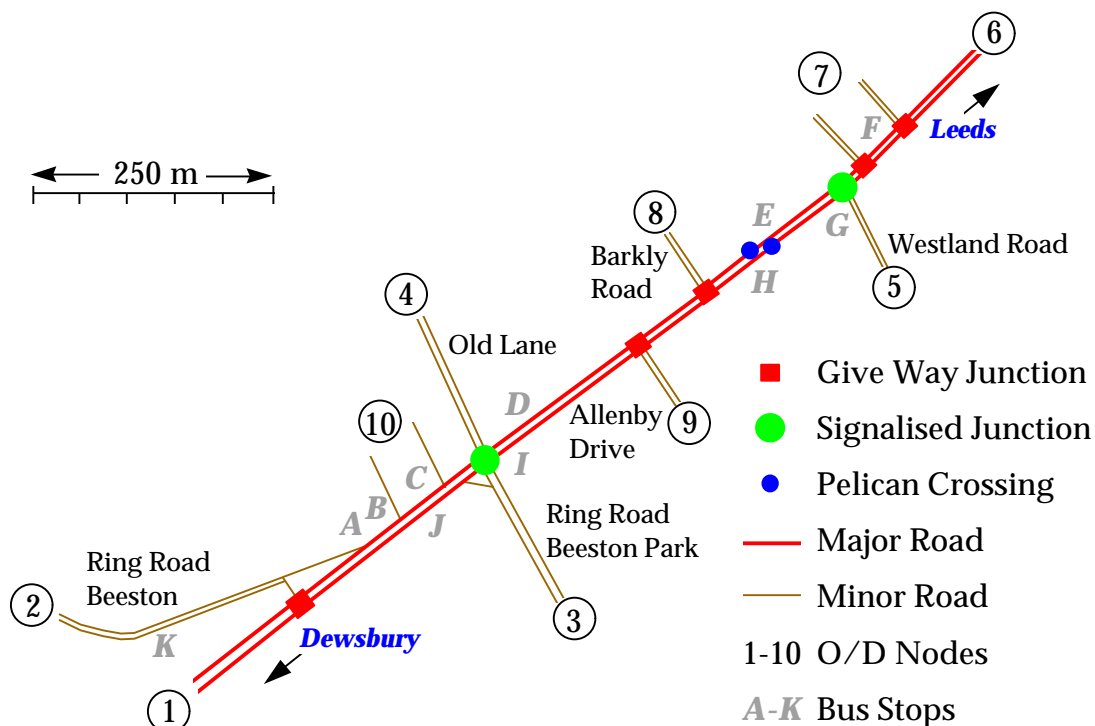


Figure 1: The Dewsbury Road - Leeds

A network in Leeds was chosen for this study because of the ready availability of suitable data to both define the network and to compare against model outputs. This

data had been collected as part of the PRIMAVERA project (Fox et.al., 1995). PRIMAVERA developed advanced traffic management strategies for urban arterial roads. These strategies were developed with the aid of the NEMIS micro-simulation tool and then the best strategy was implemented on-street. Much data was collected, firstly to calibrate and validate the initial micro-simulation model of the network, then to evaluate the effectiveness of the new strategies on-street. Data was collected for both AM and PM Peak periods. The full PRIMAVERA network in Leeds consisted of ten signalised intersections along 3km of an urban arterial, namely the Dewsbury Road, classified as the A653. This is one of the main radial routes into Leeds, carrying approximately 23,000 vehicles per day. It is also a heavily used public transport corridor, peak bus flows being in excess of 36 buses per hour.

To simplify the transferability tests carried out by the SMARTTEST project, a sub-network of the PRIMAVERA network was used. This consisted of a 1½ km segment of the Dewsbury Road, containing two signalised junctions and a pelican crossing (see Figure 1). The test network also contains a number of priority junctions, where minor roads join the main arterial. Bus stops are also present in the network. The network thus contains many features which are common in urban road networks in the UK. An additional feature of the test network is that there is only one route between each of the origin destination pairs, therefore route choice is not an issue to cloud the model evaluation. It was also decided to only carry out simulation runs of the AM peak period.

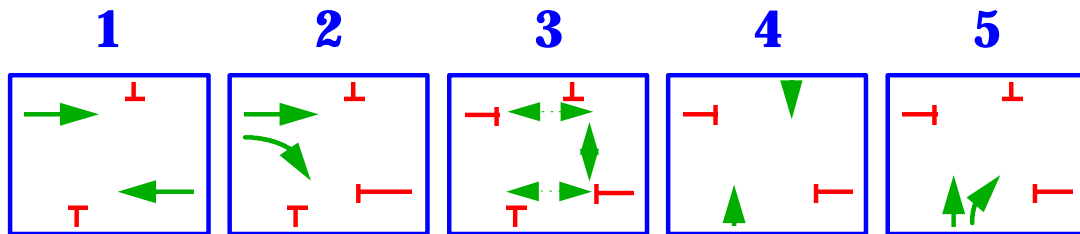
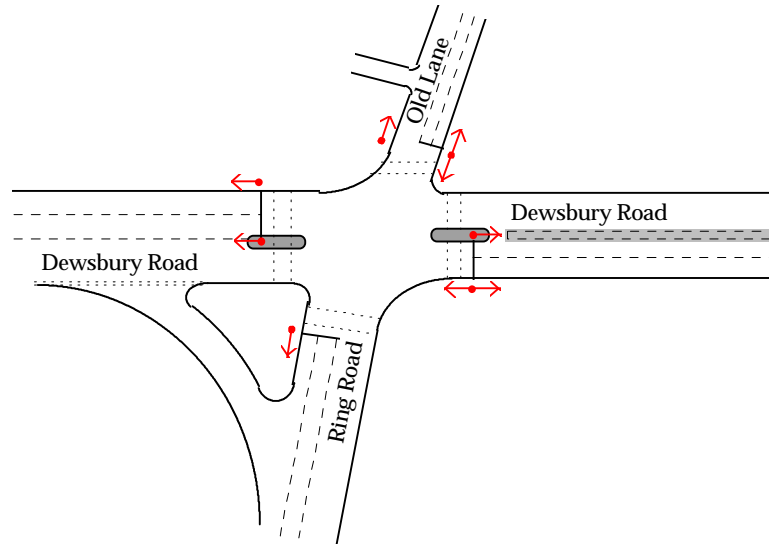


Figure 2: Old Lane / Ring Road Beeston Park Junction

The main signalised junction in the network is where Old Lane and the Ring Road Beeston Park meet the Dewsbury Road. This is a four arm junction with pedestrian facilities (see Figure 2). All the approaches are signalised, however the left turn from the Ring Road onto the Dewsbury Road is an unsignalised slip road. There are bus routes along each of the four arms of the junction.

The other signalised junction in the network is a three arm junction where Westland Road joins the Dewsbury Road (see Figure 3).

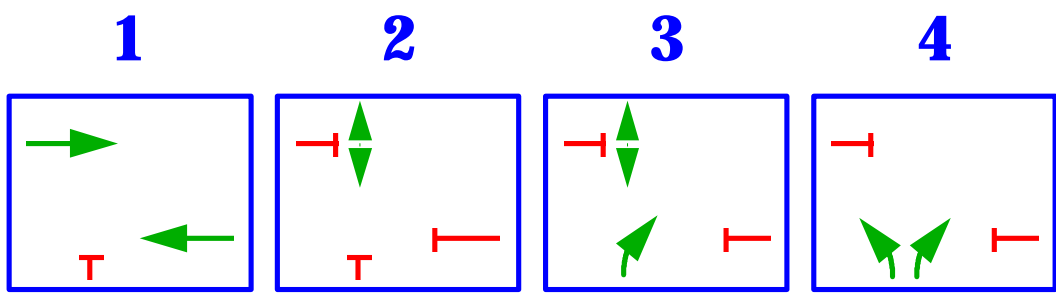
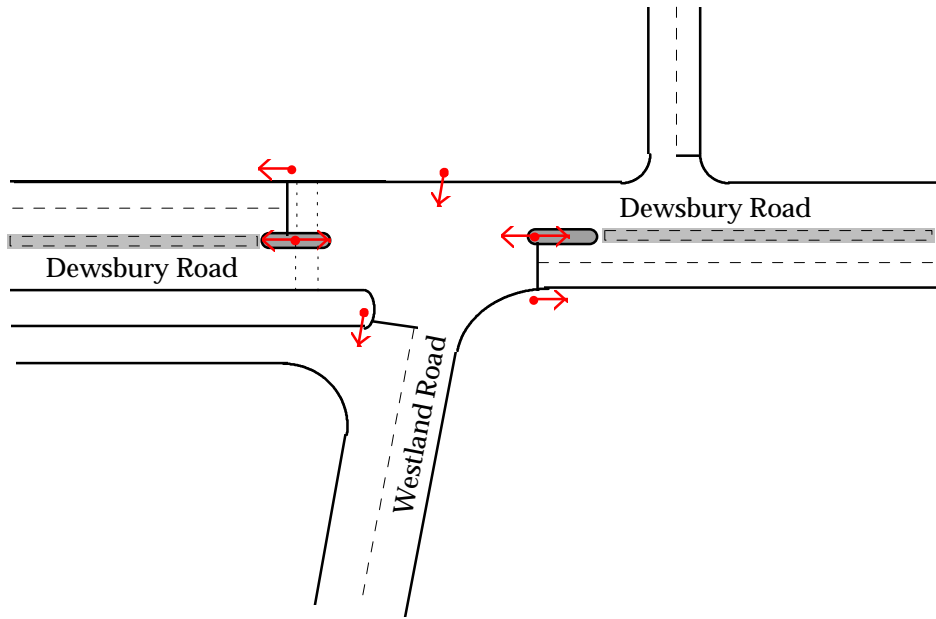


Figure 3: Westland Road Junction

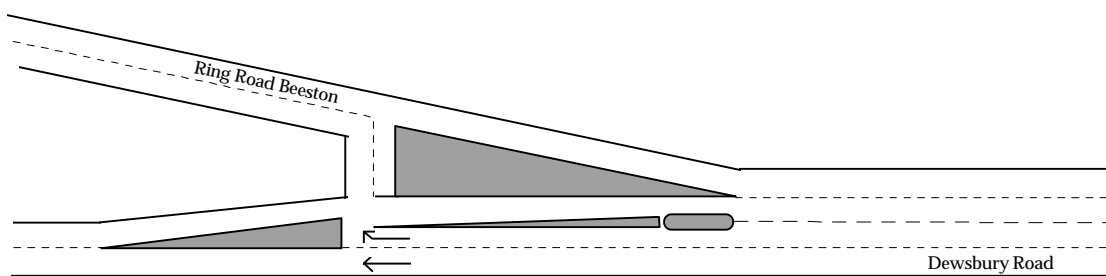


Figure 4: Junction with Ring Road Beeston

The major non-signalised junction in the network is at the south western end where the Ring Road Beeston merges with the Dewsbury Road. This is a quite complicated priority junction. There are separate lanes reserved for right turns from the Dewsbury Road into the Ring Road Beeston and for both left and right turns out of Ring Road Beeston on to the Dewsbury Road (see Figure 4).

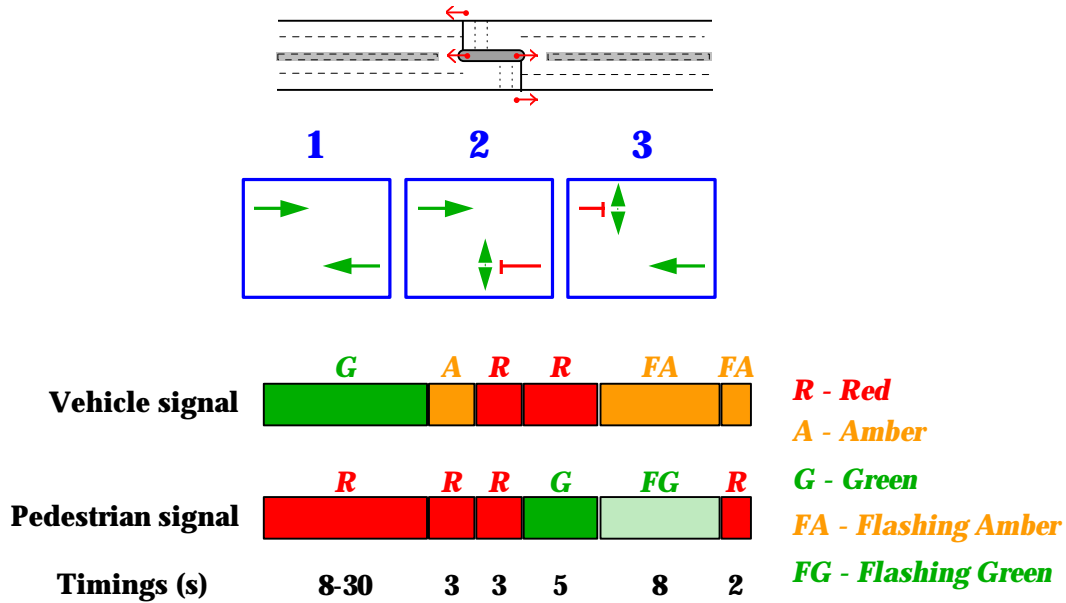


Figure 5: Barkly Road Pelican

There is also a staggered pelican crossing in the network. It is on the Dewsbury Road close to Barkly Road (see Figure 5).

Although the PRIMAVERA project developed traffic management strategies that utilised the SCOOT and SPOT adaptive signal control systems, at times the network also operated using signals controlled by fixed time plans. The data used for the SMARTTEST transferability tests only related to those periods where the network was under fixed time control. These fixed time plans are given in Table 1. These include the cycle times and offsets and the durations of each phase and intergreen period in seconds. See each of the junction diagrams for details of movements associated with each phase.

Junction	Cycle Time	Offset	1	I	2	I	3	I	4	I	5	I
1	88	34	40	4	4	11	7	8	7	4	4	7
2	88	20	63	6	8	6			10	5		

Junction 1: Old Lane. Junction 4: Westland Road.

Table 1: AM Peak fixed time plans

Note that the Barkly Road pelicans are double cycled, i.e. they have a cycle time half of that for the rest of the network.

Bus routes go between many of the origin and destination nodes in the network. The bus routes associated with each origin and destination pair, along with their scheduled entry times at each origin during the AM Peak hour are shown in Table 2.

O	D	Buses	Route Number(Origin Start Times)
1	6	15	46(15,45), 117(5), 118(44), 201(10), 202(42), 203(25,55), 218(11), 220(41,51), 222(35), 226(26), X7(5), X16(20)
2	3	2	9(0,36)
2	6	4	2(0,15,30,45)
3	2	2	8(10,34)
3	4	2	74(0,30)
3	6	12	3(9,24,39,54), 24(4,34), 25(17,47), 77(11,41), 484(19,29)
4	3	2	74(19,54)
6	1	12	46(27,57), 117(43), 118(15), 201(26), 202(56), 203(11,41), 218(13), 220(43), 222(3), 226(0)
6	2	4	2(0,15,30,45)
6	3	10	3(8,23,37,52), 24(19,49), 25(4,34), 77(22,52)

Table 2: Bus Routes, frequencies and starting times during the AM Peak hour

Data Collected

Much data was collected during the PRIMAVERA project. In addition, a digital map of the area was available in AutoCAD format, which allowed the network geometry to be easily and accurately measured. The surveys carried out are summarised in Figure 6.

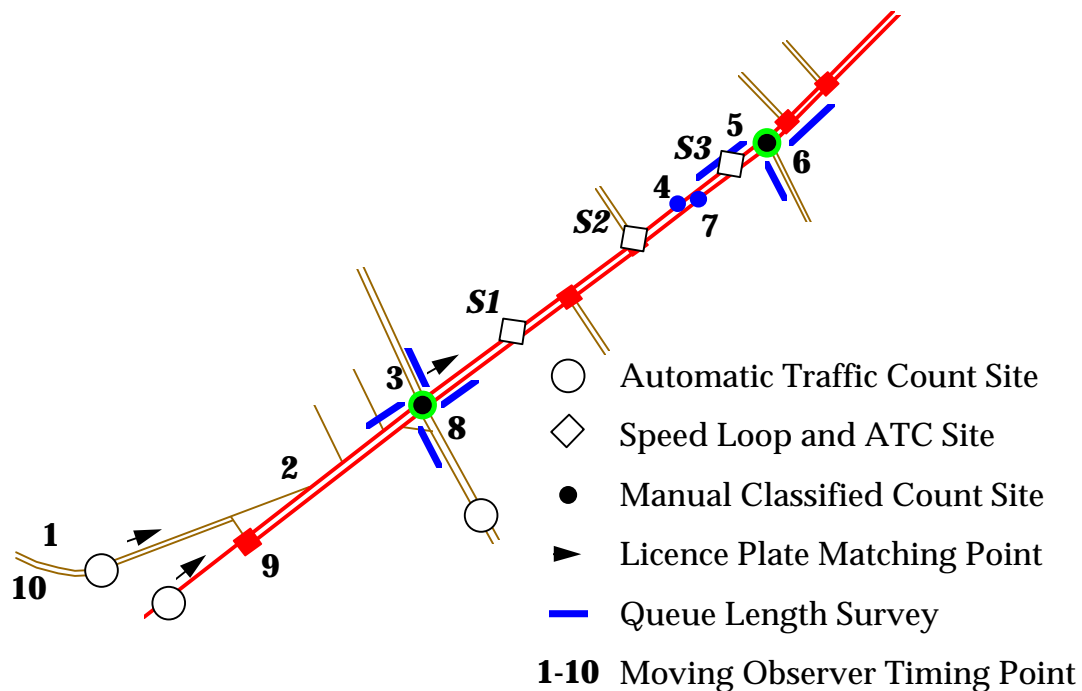


Figure 6: Field Trial Data Collection

Statistical analysis has been used to estimate the accuracy of the collected data. When comparing simulation outputs with data collected from the real world it is important to ensure that sufficient data has been collected to estimate the values being compared to a desired accuracy. If the usual statistical assumptions are made regarding the normality of the data then it is possible to determine the confidence interval for a population mean. The confidence interval is a range on either side of the sample mean. It is expressed as a function of a significance level, α , which usually has a value of 95%, and is given by the formula:

$$(t_L, t_U) = \left(\bar{x} - z_{1-\alpha/2} \frac{\mathbf{S}}{\sqrt{n}}, \bar{x} + z_{1-\alpha/2} \frac{\mathbf{S}}{\sqrt{n}} \right) \quad (1)$$

where $z_{1-\alpha/2}$ is that value in the standard distribution that has $1-\alpha/2$ area to the left. For a 95% confidence level, $\alpha = 0.05$ and $z_{1-\alpha/2} = z_{0.975} = 1.96$.

The surveys on the PRIMAVERA network included:

- Automatic Traffic Counts, using loops, to measure traffic flows in both directions at three points in the network.
- Automatic Speed and Flow measurements as vehicles passed over at three data collection points on the Dewsbury Road.
- Manual Classified Counts at two of the junctions, to obtain turning movements for seven categories of vehicle.
- Travel time surveys both by number plate matching at three points in the network and by moving observers travelling in cars and buses around the network.
- Queue length surveys were carried out at the two signalised intersections.
- Bus waiting times at stops were measured by observers.

Flow Data

The Automatic Traffic Counts and the Manual Classified Counts have been combined to produce two Origin/Destination matrices for the AM Peak hour. The first matrix is for cars, the second for heavy goods vehicles (HGVs). These can be seen in Table 3 and Table 4.

	1	2	3	4	5	6	7	8	9	10	Total
1	-	-	90	26	32	470	25	30	30	-	703
2	-	-	50	13	16	240	10	15	15	-	359
3	110	110	-	241	40	230	5	5	-	-	741
4	22	22	215	-	10	50	-	-	5	-	324
5	12	12	5	1	-	80	5	-	-	-	115
6	150	180	100	10	200	-	25	-	30	-	695
7	10	10	5	-	10	25	-	-	-	-	60
8	-	-	-	-	25	150	-	-	-	-	175
9	10	10	5	5	5	25	-	-	-	-	60
10	-	-	-	-	-	50	-	-	-	-	50
Total	314	344	470	296	338	1320	70	50	80	0	

Table 3: The Car O/D Matrix for the AM Peak hour

	1	2	3	4	5	6	7	8	9	10	<i>Total</i>
1	-	-	4	1	4	11	-	-	-	-	20
2	-	-	3	-	4	12	-	-	-	-	19
3	8	2	-	-	-	10	-	-	-	-	20
4	-	-	-	-	-	1	-	-	-	-	1
5	5	1	-	-	-	17	-	-	-	-	23
6	8	3	10	4	4	-	-	-	-	-	29
7	-	-	-	-	-	-	-	-	-	-	0
8	-	-	-	-	-	-	-	-	-	-	0
9	-	-	-	-	-	-	-	-	-	-	0
10	-	-	-	-	-	-	-	-	-	-	0
<i>Total</i>	21	6	17	5	12	51	0	0	0	0	

Table 4: The HGV O/D Matrix for the AM Peak hour

Car Travel Time Data

Two “moving observers” were used to collect travel time data in the network. Staff drove a car round two defined routes and noted times as they passed specific timing points (see Figure 6). Data was collected on five weekdays in July and three weekdays in October 1994. The data relevant for the AM peak is presented in Table 5. This identifies the times between the various timing points, the number of observations (n), the mean travel time (seconds), the standard deviation of the travel time (seconds), the 95% confidence interval as given by equation (1), and the distance between the timing points (metres).

Link	n	Mean (s)	s.d.	C.I.	Length (m)
1-2	50	41.0	9.79	(38.3,43.7)	469
2-3	51	63.0	32.39	(54.1,71.9)	196
3-4	98	36.1	4.37	((35.2,37.0)	493
4-5	100	24.6	11.75	(22.3,26.9)	185
6-7	99	13.7	2.91	(13.1,14.3)	193
7-8	100	56.3	23.53	(51.6,60.9)	480
8-9	98	34.0	15.53	(30.9,37.1)	270
9-10	100	55.6	19.59	(51.7,59.4)	430

Table 5: Car Travel Times AM Peak (Moving Observers)

Bus Travel Time Data

Moving observers were also used to collect bus travel times in the network. Unfortunately in the sub network used for the transferability study they only covered times between the Westland Road junction and the Barkly Road pelican. These journey times can be seen in Table 6. It should be noted that there is bus stop between these junctions in both directions.

Link	n	Mean (s)	s.d.	C.I.	Length(m)
4-5				(,)	185
6-7	25	41.2	12.8	(36.1,46.2)	193

Table 6: Bus travel times AM peak

Data was also collected on waiting times at most of the bus stops in the network this can be seen in Table 7 (see Figure 1 for the bus stop identifiers).

	B	C	D	E	F	G	I	J	K
Mean (s)	7.0	7.7	34.1	14.6	29.7	11.0	5.0	18.0	6.0

Table 7: Mean Waiting Times at Bus Stops

Speed Data

Speed count data was collected at three points in the network, either side of Barkly Road pelican. These are designated S1, S2 and S3 in Figure 6. The speed count detectors counted the number of vehicles travelling in given speed bins. The speed profiles thus generated during the AM peak are given in Figure 7. The speed limit for this section of the Dewsbury Road is 40 mph. As can be seen, a significant number of vehicles exceed the speed limit here (13% at S1, 16% at S2 and 4% at S3).

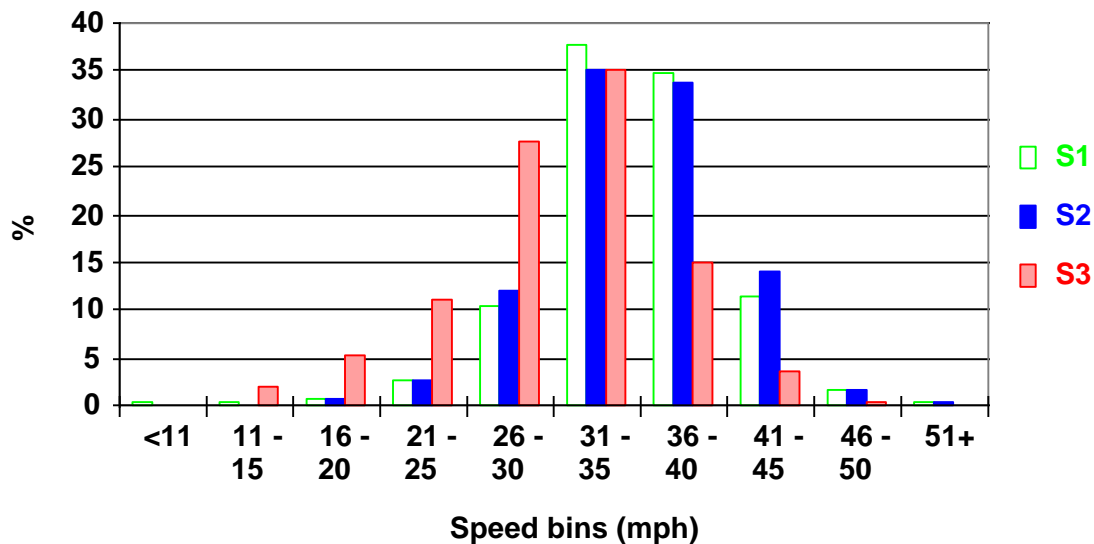


Figure 7: Speed Profiles at Barkly Road

The mean speeds at each of the three speed count detectors during the morning peak hour is given in Table 8, as is the standard deviation (s.d.), number of observations (n) and the confidence interval (C.I.) given by equation (1).

Detector	Mean Speed (mph)	s.d.	n	C.I.
S1	35.1	5.62	2970	(34.9,35.3)
S2	35.4	5.45	3603	(35.2,35.6)
S3	30.5	6.31	1800	(30.2,30.7)

Table 8: Mean speeds at the detectors (AM Peak)

Queue Data

Queue surveys were carried out at the two signalised intersections in the network during the AM peak. Queue lengths were defined by the number of vehicles waiting at the moment the signals changed to green. The queues for the Old Lane / Ring Road

Beeston Park junction can be seen in Figure 8. Unfortunately the queue on the Ring Road arm often extended beyond the visibility of the observer.

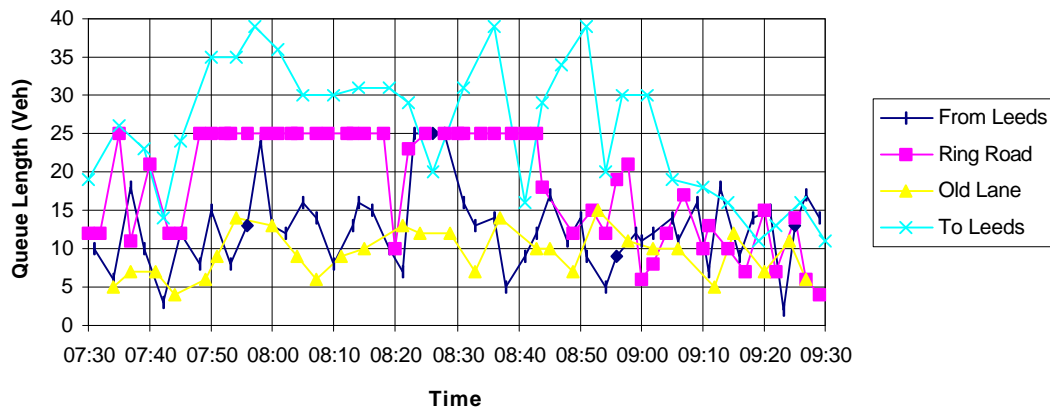


Figure 8: Queues on the Old Lane / Ring Road Beeston Park junction (AM Peak)

Figure 9 shows the queues on the Westland Road junction. Once again there were times when the queues on one of the arms (Dewsbury Road traffic going to Leeds) extended beyond the visibility of the observer.

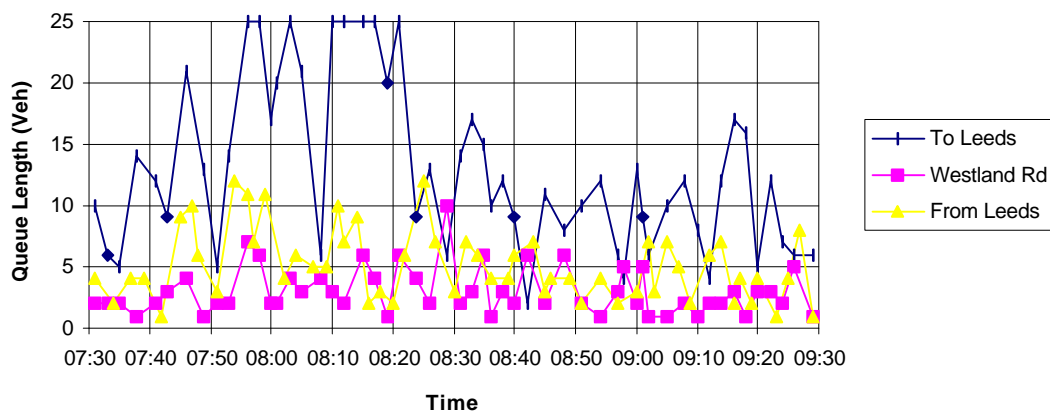


Figure 9: Queues on the Westland Road junction (AM Peak)

The data relevant for the arms where the queue was always fully observed are shown in Table 9. This identifies the various arms, the mean queue (vehicles), the standard deviation of the queue (vehicles), the number of observations (n) and the 95% confidence interval as given by equation (1).

	Mean	s.d.	n	C.I.
Old Lane Junction				
To Leeds	25.6	8.75	31	(22.5,28.7)
From Leeds	12.6	5.17	51	(11.2,14.1)
Old Lane	9.3	3.04	29	(8.2,10.5)
Westland Rd Junction				
From Leeds	5.2	2.87	53	(4.4,6.0)
Westland Rd	3.0	1.92	55	(2.5,3.5)

Table 9: Mean Queue Lengths

MODELLING APPROACHES

Network Geometry

All three micro-simulation models used similar network representations. Junctions are represented by nodes, and nodes are connected by links, each with a number of lanes.

Separate links are required for travel in each direction, i.e. none of the models allowed two-way movement on a link. This limitation can be important as it prevents overtaking via the oncoming lane if there is a suitable gap.

NEMIS has a minor limitation in that it can only model road networks where traffic usually drives on the right, so to model the UK network a mirror image has to be used. NEMIS also has a limit of four arms to a junction.

NEMIS is the only model that has provision for on-street parking.

AIMSUN2 has a very user friendly network builder that allows AutoCAD maps to be used as backgrounds. The road network model is then drawn over the top of this map. This allows an accurate network geometry to be specified without fear of error. AIMSUN2 was therefore the first model used to code up the Dewsbury Road network. The link lengths and their positions obtained from the AIMSUN2 model were then used to code up the NEMIS and DRACULA network models.

Car-Following and Lane Changing

Driver behaviour is modelled via a car following rule and gap acceptance and overtaking rules. These usually have parameters which characterise desired headways, reaction times, aggressiveness, awareness and acceptable gaps for lane changing and turning across opposing traffic flows. Due to difficulties in measuring these parameters few of them are ever measured directly. The modeller relies on indirect measurements such as average headways, lane usage or saturation flow measurements to justify the values used.

AIMSUN2 uses a car following law based on that suggested by Gipps (1981) and a lane changing rule based on Gipps (1986). NEMIS uses a different car-following law, based on a study by Donati and Largoni (1976). Key parameters for four different vehicle types have been determined.

Vehicle Types

Both NEMIS and DRACULA have a limit on the number of vehicle types allowed. DRACULA is limited to six types, namely Cars, Buses, Guided Buses, Taxis, High Occupancy Vehicles and Heavy Goods Vehicles. NEMIS allows seven types, namely five different types of private vehicle, plus buses and trams. AIMSUN2 allows multiple vehicle types to be specified.

Each vehicle type has associated with it a fixed set of parameters, such as acceleration and deceleration rates, vehicle length and car following parameters. Table 10 gives

some of the default parameters provided for the various vehicle types used by each of the models.

DRACULA	Car	Bus		
Maximum Acceleration (m/s/s)	2.5	2.5		
Maximum Deceleration (m/s/s)	2.5	2.5		
Length (m)	3.5	7.5		

AIMSUN2	Car	Truck	Bus	Long Truck
Maximum Acceleration (m/s/s)	2.8	1.0	2.0	1.0
Maximum Deceleration (m/s/s)	4.0	3.5	3.0	3.5
Length (m)	4.0	8.0	9.0	12.0
Desired Speed (km/h)	90	70	60	70

NEMIS	All vehicles
Maximum Acceleration (m/s/s)	3.0
Maximum Deceleration (m/s/s)	5.0
Maximum Speed (km/h)	50.4

Table 10: Some default micro-simulation motion parameters

Public Transport

The main drawback of AIMSUN2 is that it does not currently directly model public transport. Although it is possible to model a bus vehicle type, it is not possible to specify routes or bus stops. This can be very important in urban networks where it is often difficult for other traffic to overtake buses at stops. Buses can therefore have a significant effect on traffic flow in the network.

DRACULA and NEMIS allow both bus routes and bus stops to be specified. Both specify the routes by defining a list of links to be followed. Both use a start time and a generation frequency to produce the bus schedules.

For DRACULA bus stops are associated with bus services. For NEMIS the stops on a route can be used by any of services that use the route. Both allow multiple stops on a link. DRACULA uses a simple wait time model for the bus stops based on a passenger arrival rate, although this is not service dependent. NEMIS just has a stop time based on a sample from a normal distribution of a fixed mean and standard deviation.

Traffic Flows

All three models have the ability to accept traffic flow data in the form of Origin / Destination (O/D) matrices. AIMSUN2 and NEMIS have built in route choice models. DRACULA uses the SATURN assignment model (Van Vliet, 1982) to calculate vehicle routes.

The vehicle generation models in DRACULA and AIMSUN2 assign an origin, destination and route to each vehicle as they are generated. NEMIS uses the results of its assignment model to produce turning percentages at each junction. So when a

vehicle arrives at a junction, a random choice is made, based on the known turning proportions, to choose the direction the vehicle is to make.

AIMSUN2 is the only model that allows different O/D matrices for different vehicle types. This could be an important factor in the Leeds network, where HGVs have a slightly different O/D pattern to other vehicle types.

Traffic Signals

All the models have the capability of modelling traffic signals operating under fixed time control.

The pelican crossing can be modelled as a two arm junction with 1 stage and a long intergreen. None of the models directly allow the demand response feature of the pelican crossing to be modelled (or other demand responsive features that may be present at other signalised junctions in the network). Pelican crossings only show red to the traffic if a pedestrian has pressed a button to register their desire to cross the road. AIMSUN2 does have the ability to allow an external module to be developed to control signals in the network so it would be possible to write such a module (as a dynamic link library) to model the correct actions of a pelican crossing. Time constraints have however not allowed such a development. It has therefore been decided that as during the AM peak it is likely that the pelican crossing will be used nearly every cycle, it can be modelled as if it was used every cycle.

INITIAL SIMULATION RESULTS

The Leeds network has been coded up for each of the three micro-simulation models. Initial calibration and validation has been carried out. A full comparison of the outputs from each of the models will be made in the UTSG conference presentation.

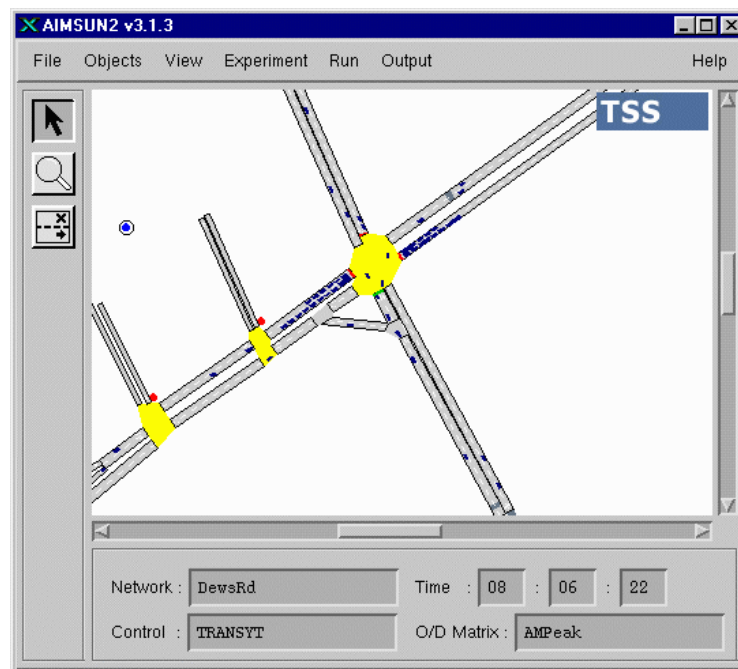


Figure 10: AIMSUN2 simulating the Leeds network

CONCLUSIONS

A variety of traffic data has been collected from a small urban road network in Leeds. This data has been processed and analysed so that it can be used in the calibration and validation of road traffic micro-simulation models.

Three micro-simulation models, initially developed to model traffic in different parts of Europe, have been used to model the traffic in the Leeds network. None of the models could represent all the features found in the test network, so some modelling assumptions had to be made to cover these cases.

The ability of the models to produce accurate representations of traffic behaviour is being investigated.

REFERENCES

DONATI, F. AND LARGONI (1976) Analisi del comportamento di una colonna di autoveicoli in condizioni perturbate, *Riunione Annuale AEL*, Sorrento, 1976.

FERRER, J.L. AND BARCELO, J. (1992) *Modelos microscopicos de simulacion de sistemas de guiado de veh'culos*. Research Report. Laboratori d'Investigació Operativa i Simulació, Universitat Politècnica de Catalunya.

FOX, K., MONTGOMERY, F.O. AND MAY, A.D. (1995a) Integrated strategies for urban arterials: DRIVE II project PRIMAVERA. 1: Overview *Traffic Engineering and Control*, **36**(5), pp268-271.

GIPPS, P.G. (1981) A behavioural car-following model for computer simulation. *Transportation Research Board*, **15-B**, pp. 105-111.

GIPPS, P.G. (1986) A model for the structure of lane-changing decisions. *Transportation Research Board*, **20-B**, pp. 403-414.

LIU, R., VAN VLIET, D. AND WATLING, D.P. (1995) DRACULA - Microscopic Day-to-Day Dynamic Modelling of Traffic Assignment and Simulation, Paper presented at the *Fourth International Conference on Applications of Advanced Technologies in Transportation Engineering*, Capri, Italy, 27-30 June 1995.

MAURO, V. (1991) Evaluation of dynamic network control: simulation results using NEMIS urban micro-simulator *Transportation Research Board Annual Meeting*, Washington DC.

VAN VLIET, D. (1982) "SATURN - A Modern Assignment Model", *Traffic Engineering and Control*, **23**, pp578-581.