Article:
Liu, R. and Tate, J.E. (2004) Network effects of intelligent speed adaptation systems. Transportation, 31 (3). pp. 297-325. ISSN 1572-9435

DOI: 10.1023/B:PORT.0000025394.78857.13

Published paper
Liu, R.; Tate, J.E. - 2004- *Network effects of intelligent speed adaptation systems* – Transportation 31(3) pp.297-325

NETWORK EFFECTS OF INTELLIGENT SPEED ADAPTATION SYSTEMS[1]

Ronghui Liu and James Tate
Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, U.K.
(E-mail: rliu@its.leeds.ac.uk; jtate@its.leeds.ac.uk)

Key words: intelligent speed adaptation, driver support systems, dynamic network modelling, microsimulation, congestion.

ABSTRACT. Intelligent Speed Adaptation (ISA) systems use in-vehicle electronic devices to enable the speed of vehicles to be regulated externally. They are increasingly appreciated as a flexible method for speed management and control, particularly in urban areas. On-road trials using a small numbers of ISA equipped vehicles have been carried out in Sweden, the Netherlands, Spain and the UK. This paper describes the developments made to enhance a traffic microsimulation model in order to represent ISA implemented across a network and their impact on the networks. The simulation modelling of the control system is carried out on a real-world urban network, and the impacts on traffic congestion, speed distribution and the environment assessed. The results show that ISA systems are more effective in less congested traffic conditions. Momentary high speeds in traffic are effectively suppressed, resulting in a reduction in speed variation which is likely to have a positive impact on safety. Whilst ISA reduces excessive traffic speeds in the network, it does not affect average journey times. In particular, the total vehicle-hours travelling at speeds below 10 km/hr have not changed, indicating that the speed control had not induced more slow-moving queues to the network. A significant, eight percent, reduction in fuel consumption was found with full ISA penetration. These results are in accordance with those from field trials and they provide the basis for cost-benefit analyses on introducing ISA into the vehicle fleet. Contrary to earlier findings from the Swedish ISA road trials, these network simulations showed that ISA had no significant effect on emission of gaseous pollutants CO, NOx and HC. Further research is planned to investigate the impact on emission with a more comprehensive and up to date modal emission factor database.

1. Introduction

Management of vehicle speed has a direct impact on road safety. Studies have long suggested that reduced speeds and lower speed variance result in fewer accidents (e.g. Munden, 1967; Hauer, 1971; West & Dunn, 1971; Salusjärvi, 1981; Garber & Gadirau, 1988; Pasanen & Salmivaara, 1993; Finch et al, 1994; Anderson et al., 1995). Recently there has been a growing interest in the potential of ISA, also know as External Vehicle Speed Control (EVSC). The system is a technical device fitted to a vehicle enabling the speed of the vehicle to be externally regulated. The external activation is achieved by a communication infrastructure in the form of roadside beacons or an autonomous system using on-board digital maps combined with a Global Positioning System. ISA systems are aimed at increasing the comfort level of driving and improving the performance by controlling the

[1] Paper accepted for publication in *Transportation*, 2003.

speed of ISA vehicles to, or advising the drivers of ISA vehicles of, the prevailing speed limits (Hoogendoorn & Minderhoud, 2002).

The main advantage of ISA systems relative to other forms of urban speed control measures, such as 20mph zones (e.g. Hodge, 1992) or traffic calming measures (e.g. Barbosa et al., 2000), is their flexibility. The systems allow for different control speeds at different times of day and different locations, for example outside schools and during school starting and finishing times. Different speeds can also be set for different traffic, roadway and weather conditions. The systems were designed originally as a speed management measure for the urban environment (e.g. Várhelyi & Mäkinen, 2001; Hoogendoorn & Minderhoud, 2002). However, there is no technical restriction to the systems being applied on motorways where they can work in similar manner as controls by variable speed signs (Webb, 1980). In this latter application, the systems aim to improve stability and homogeneity of traffic flow in order to reduce interactions and hence potential conflicts among vehicles, which in turn reduce accidents.

On-road trials of ISA systems were first conducted in Sweden (Almquist et al. 1991; Almquist & Nygård, 1997) and later in the Netherlands and Spain (Várhelyi & Mäkinen, 2001). The speed control proved very popular, especially near schools. They were shown to affect driver behaviour and result in lower average vehicle speeds. More extensive trials have been subsequently carried out in four Swedish cities with several thousand vehicles equipped with an ISA system (Lind, 1999). The major benefits of the system were found to be on safety, reduction in emissions and improved use of road space (Martin, 2002).

In spite of its great potential, this area has attracted very little research attention. Much of the discussion has been focused on the systems' design specification (e.g. Carsten & Comte, 1997; Dahlstedt, 1994; Kulmala, 1996), public acceptance (e.g. Várhelyi, 1996; Comte et al., 2000) and driver comfort (e.g. Comte, 2000). These studies have been carried out through driving simulator experiments and/or actual road trials which, by their very nature, are limited in system penetration rates and traffic conditions (Várhelyi & Mäkinen, 2001). Network simulation modelling, on the other hand, provides a cost-effective method and controlled environment for evaluating the control systems in a network context. It is particularly useful for studying the complicated interactions between equipped and non-equipped vehicles during transition periods. Microsimulation modelling has been carried out to analyse the effect of ISA on road capacity and traffic flow stability over a single stretch of highway (e.g. Alkim et al, 2000; Hoogendoorn & Minderhoud, 2002). There appears to be no systematic analysis of the effect of ISA on *network-wide* efficiency and of driver behaviour in complex interactions (e.g. junction control and blocking-back).

This study was part of a research program funded by the UK Department for Transport to investigate the benefits or dis-benefits and driver behaviour under various ISA control systems, and to seek the most effective mechanism of integrating ISA into the UK market. The objectives of the research were to:

1. Review previous and current research on ISA. Assess a number of potential alternatives in implementing ISA, with particular focus on the costs and benefits of the system compared with traditional speed reduction measures;
2. Identify major alternative approaches for system implementation. Design and build a test vehicle enacting these speed control systems;

3. Study these systems in-depth with driving simulator experiments and on-road trials to investigate the safety benefits and driver behavioural adaptation effects;
4. Examine the network effects and benefits of these systems on various types of road and traffic conditions using a traffic microsimulation model;
5. Select the most appropriate control system to realize the best combination of benefits to traffic management and accident risk based on studies 3 and 4, and produce recommendations on the implementation of the system.

Findings on issues 1-3 above have been reported in Carsten and Comte (1997) and Comte (2000). This paper describes the developments made to enhance the traffic network microsimulation model DRACULA (Liu et al, 1995) to meet the fourth task above. The model was suitably adapted to explicitly represent the driving behaviour under ISA. Simulation modelling of the ISA system was carried out on two real-world networks to examine the control impacts under different levels of congestion. Together with its fuel consumption and emission models, DRACULA was used to provide traffic performance measures (e.g. travel time, speed, flow, queue) and environmental indicator (in terms of exhaust emissions and fuel consumption) for a wide range of ISA penetrations.

Section 2 of the paper outlines the method in selecting the ISA system for the simulation analysis. Sections 3 and 4 describe the modelling techniques developed to represent driver behaviour under ISA. Results from the simulation of the ISA system in two urban environments are presented in Section 5. Finally Section 6 draws conclusions and presents directions for further research.

2. The Study Design

Earlier project work has identified two main categories of ISA implementations in which vehicle speed is controlled (Carsten & Comte, 1997):

1. "Mandatory systems" which automatically limit a vehicle's maximum speed to either a prevailing fixed speed limit or to a speed limit varying with road geometry;

2. "Voluntary systems" which provide speed limit warnings to the driver, and allow the driver to make their own decision, as to whether to act upon the warning. Driver compliance can be achieved either through the normal use of the vehicle control (the "advisory systems") or by driver enacting the changes, say, by pressing a button to allow the vehicle's speed be regulated to the speed limit (the "driver selection systems").

There are two types of mandatory systems: a fixed system which adapts a set of fixed, legal speed limits and a variable system in which the speed limit is a continuous function in space. The variable systems allow smooth speed reduction to account for poor geometry and the like. Both types of mandatory systems and a driver selection system were studied in the project with a driving simulator and on-road trials. Findings of these studies on driver safety are presented in Comte (2000).

To model the voluntary systems in a network context would introduce a great number of unknowns, with regard to the parameters of drivers' decision to comply with the speed warning and would therefore require some sensitivity testing. For this reason, only the mandatory systems were represented in the model and a variable mandatory system analysed in the network simulation study whereby the maximum speed is mandatory and drivers have no choice but to comply.

For the purpose of evaluating network performance, a more useful distinction is the actual number (or percentage) of vehicles complying with the speed limits (being it mandatory or voluntary) and the speed limits on each section of the road. The speed limits are inputs to the simulation modelling; they can easily take into account road geometry (to represent the variable mandatory systems). The speed limits can vary with locations but are fixed over the study time periods.

In the simulation modelling, the ISA systems are to be examined for their effects under:

(i) different traffic conditions: congested or non-congested;
(ii) various levels of system penetration, in order to represent the transition period when only new vehicles could be equipped with ISA and to investigate the interactions between equipped and non-equipped vehicles; and
(iii) variable speed limits.

For these purposes, only an individual vehicle second-by-second network simulation model can fully represent the technology envisaged for ISA. The dynamic microsimulation model DRACULA developed at Leeds was selected so that specification of ISA systems and driver behaviour under the control can be readily incorporated.

3. The DRACULA Microsimulation Model

DRACULA (Dynamic Route Assignment Combining User Learning and microsimulAtion) is a day-to-day, microscopic suite of urban traffic assignment and simulation models (Liu et al., 1995). It incorporates a microscopic demand model, which represents individual drivers' learning and daily route and departure time choice behaviour, with a microscopic traffic model which simulates individual vehicle movements through the network. In the present study, the emphasis is on the simulation of the different driving behaviour under ISA control and the impact on network performance. The traffic microsimulation part of the model suite was adapted to model ISA, with fixed route choices given as an input to the simulation. The potential impact of ISA on drivers' route and departure-time choices will be investigated in a later study.

3.1 Traffic simulation

The traffic simulation model is based on a fixed-time increment, with the speeds and positions of each vehicle updated every one second. Vehicles are individually characterised, including a technical description of the vehicle (vehicle type, length, maximum acceleration and deceleration) and behaviour of the driver (reaction time, desired speed and distance from the vehicle in front). These characteristics are randomly sampled from normal distributed representations of the type of vehicle, with means and coefficients of variation defined by the user. Section 4.2 describes the introduction of a new vehicle class in the model to represent ISA-controlled vehicles.

Vehicles follow pre-defined fixed routes through the network, derived externally from either the microscopic assignment model of DRACULA or from an equilibrium assignment model such as SATURN (Van Vliet, 1982). They are moved in real-time and their space-time trajectories are determined by their desired movements, the traffic regulations on the road and interactions with neighbouring vehicles through car-following, lane-changing and gap-acceptance models. The main changes in driving behaviour adapted for ISA vehicles are their car-following behaviour (see Section 4.1). The car-following model for non-ISA controlled vehicles is described below. Detailed description of the lane-changing and gap-acceptance models developed for DRACULA can be found in Liu (2003).

The car-following model attempts to mimic drivers' desired movements and their interactions with the vehicles in front according to the relative distance away from the preceding vehicle. Normally, a driver applies a controlled acceleration which is related to the speed and space differences between their own vehicle and the one they are following. Thus, where a vehicle is very close to the one in front, the driver would be prepared to slow in case the preceding vehicle brakes suddenly. The Gipps close-following model (Gipps, 1981) is adopted here where the following vehicle keeps at a safe speed in anticipation of the sudden deceleration from the vehicle in front:

$$v_n^{close}(t+\tau_n) \le d_n\tau_n + \sqrt{d_n^2\tau_n^2 - d_n\{2[x_{n-1}(t) - x_n(t) - L_{n-1} - s_n^{\min}] - v_n(t)\tau_n - v_{n-1}^2(t)/d'_{n-1}\}} \quad (1)$$

where n and n-1 denote the subject and its preceding vehicle, v and x the speed and position of the vehicles. τ_n is the reaction time, s_n^{min} the minimum safety distance, and d_n the deceleration of vehicle n. d'_{n-1} is the deceleration of vehicle n-1 perceived by vehicle n, and L_{n-1} the length of vehicle n-1.

In addition, a model based on Mauro (1991) is incorporated to represent a more "relaxed" following situation where the following vehicle is not expecting a sudden and rapid deceleration from the vehicle in front:

$$v_n^{relaxed}(t+\tau_n) = c_1 v_n(t) + c_2 v_{n-1}(t) + c_3[x_{n-1}(t) - x_n(t) - L_{n-1} - s_n^{\min}] \quad (2)$$

where c_1, c_2 and c_3 are constant parameters.

Where a vehicle is far away from either an intersection or the vehicle in front, the driver of the vehicle is modelled as being able to accelerate freely in order to reach and maintain his/her desired speed. The Gipps free-moving speed is adopted here (Gipps, 1981):

$$v_n^{free}(t+\tau_n) = v_n(t) + 2.5a_n\tau_n(1 - v_n(t)/V_n)(0.025 + v_n(t)/V_n)^{1/2} \quad (3)$$

where a_n is the maximum acceleration of vehicle n and V_n its desired speed. The actual speed of the following vehicle n is the minimum of the three, e.g.:

$$v_n^{c-f}(t+\tau_n) = \min(v_n^{close}, v_n^{relaxed}, v_v^{free}) \quad (4)$$

3.2 The emission model

It is well known that vehicles, especially those equipped with a three-way catalyst, produce more harmful emissions when operating in the acceleration mode than when cruising mode (Andre & Pronello, 1997). Taking the simulated individual vehicles' speed and acceleration, the emission model in DRACULA considers explicitly the vehicles' four different driving modes (acceleration, deceleration, cruising and idling) and calculates emissions for pollutants Carbon monoxide (CO), Nitrogen Dioxides (NOx), and HydroCarbons (HC) based on emission factors from the European project QUARTET (QUARTET, 1992). The model assumes that emission factors are constant for vehicles waiting in a queue (idling), accelerating or decelerating. For vehicles cruising at a constant speed, the emission factors are assumed to be varying as a function of speed.

3.3 The fuel consumption model

DRACULA also calculates fuel consumption based on the fuel-consumption models of Ferreira (1982) and DOT (1991). The models assume that when vehicles are moving at constant speeds, the fuel consumption rates (litre/hour, or ml/second) increase with increasing cruising speeds. Table 1 lists the fuel consumption rates at 12 discrete cruising speeds.

Insert Table 1 here

When in acceleration, the model assumes that the fuel consumption rate (F_a) is a function of both the acceleration (a) and the speed (v), in the following form:

$$F_a = 0.42 + 0.26 \times a \times v \qquad (a > 0, v > 0) \qquad (5)$$

The model suggests that in the urban environment where most of the vehicle speeds are below 60 km/hr, the fuel consumption rates during vehicle's acceleration mode are significantly higher than those when cruising. When in cruising mode, the rates increases with increasing speeds.

The model also assumes that when vehicles are in idling and deceleration modes, the fuel consumption rates are constant at 0.333ml/sec and 0.537ml/sec respectively. It may seem counter-intuitive that the fuel consumption rate is greater during deceleration than idling. This is because that when a vehicle is idling, its engine is not under load and the revolutions per minute (RPM) are low which results in small fuel consumption rate. When a vehicle is decelerating, its engine is commonly used to assist braking with higher RPM on average than when idling and hence elevated fuel consumption rate.

3.4 Simulation outputs

Typical outputs from the DRACULA simulation model include: travel time, travel distance, speed, fuel consumption and pollutant emissions. Outputs may be reported at regular time intervals or as a summary at the end of the simulated period and may be dis-aggregated, for example by vehicle type, route chosen or for each link in the network. Individual vehicle travel times and space-time trajectories can also be accessed, to analyse issues of variability. Visual evidence is available through an on-line animation of the movements of individual vehicles through the network.

4. ISA Modelling in DRACULA

4.1 Driving behaviour

The features of ISA modelled in DRACULA are based on the design parameters for mandatory ISA systems. The important design parameters are the prevailing speed limits in the network and maximum deceleration in situations when vehicles' speeds are exceeding the speed limits or upon first entering an ISA-controlled region.

In the model, the movement of an ISA vehicle is determined not only by the car-following rule as described in Section 3, but also by the ISA speed limit in the controlled region. The latter is represented by the vehicle adjusting its speed to the speed limits as follows:

$$v_n(t+\tau_n) = \begin{cases} v_n^{c-f}(t+\tau_n) & \textit{if} \;\; v(t) \le v_0 \\ v_n(t) - d_0 & \text{otherwise} \end{cases} \tag{6}$$

where v_0 is the ISA speed limit,
d_0 a constant deceleration used by ISA vehicles to reduce their speeds, and
$v_n^{c\text{-}f}$ the speed derived from normal car-following rules (eq. (4)).

The system allows the speed of a vehicle to exceed the speed limit initially before forcing it to a speed at or below the limit. The deceleration forces applied (d_0) are such that a gentle rate of 0.5m/s^2 would result.

Outside the ISA controlled regions, drivers resume their manual control instantaneously and drive according to their normal driving behaviour. Recent studies have shown that drivers became more aggressive, such as keeping closer following, after they came out of ISA controlled region compared to their normal driving behaviour (e.g. Comte, 2000; Várhelyi & Mäkinen, 2001). This behaviour has not been incorporated in the current model. Further studies will consider such driver adaptational behaviour.

4.2 System penetration

A new vehicle class is introduced to represent whether a vehicle is equipped with an ISA device. The level of penetration is represented by the percentage of vehicles equipped with ISA; the actual ISA vehicles are then drawn randomly from the whole population according to the user-specified percentages.

4.3 ISA speed limits

The ISA speed limits on the network can be specified for a whole link or sections on a link. The latter is particularly useful in representing curved links or links with heavy pedestrian movements whereby a lower speed limits may be desirable.

5. Simulating ISA in an Urban Environment

5.1 The test scenario

The enhanced DRACULA simulation model was used to simulate an ISA system implemented across a real-world urban traffic network. The network covers two radial routes

(A64 and A63) and its neighbouring residential streets in the east of Leeds. From the outer ring road to the city centre, the network stretches over 8 km (see Figure 1). The network has 120 intersections, 245 links and 70 zones used by a peak-hour demand of 18,000 trips (which is about 20% of the total morning peak demand for the city of Leeds) and an off-peak demand of 12,000 trips. Both the morning peak and off-peak traffic conditions were simulated in order to examine the performance of ISA under different traffic congestion levels. There were 22 bus routes represented in the network served by 102 buses per hour. Both networks were extracted from the existing Leeds SATURN models developed by the local authority.

A variable mandatory speed control system was simulated. Two levels of speed limits were set according to road type: a 40 mph speed limit is set for the two radial routes and a 30 mph limit for all residential streets, in accordance with those observed on-street. In addition, on one of the entry links on the ring road, a national speed limit of 70 mph was identified. Figure 1 depicts the speed limit distribution over the network.

Insert Fig. 1 here

Area Traffic Control (ATC) counts at 7 locations and observed journey times along 18 major sections of the network were acquired from the local authority for calibrating the traffic characteristics in the base networks. Figure 2 shows the ATC count sites and journey time measurement points on the network.

Insert Tables 2 and 3 here
Insert Fig. 2 here

The SATURN assignment model was calibrated with the observed ATC counts. Tables 2 and 3 list the observed and modelled flows at each of the count sites for the off-peak and morning peak time period respectively. The modelled and observed link flows are strongly correlated with a correlation coefficient of 0.978 and 0.989 for the off-peak and morning peak respectively (see also Figure 3).

A GEH statistics (van Vliet, 2002) is also performed to obtain the goodness-of-fit measures between the modelled and observed link flows. The GEH statistics is first introduced by Geoff Harvers of the Greater London Council to compare two different values of flow on a link, V_1 and V_2. It is defined as:

$$GEH = \sqrt{(V_2 - V_1)^2 / (0.5(V_1 + V_2))} \tag{7}$$

"It can be thought of as the square root of the product of the absolute difference and the relative difference, hence overcome the inability of either the absolute difference or the relative difference to cope over a wide range of flows. For example, an absolute difference of 100 vehicles/hr may be considered a big difference if the flows are of the order of 100 vehicles/hr, but would be acceptable for flows of the order of several thousand vehicles/hr. Equally a 10% error in 100 vehicles/hr would not be important, whereas a 10% error in, say 3000 vehicles/hr might mean the difference between building an extra lane or not" (van Vliet, 2002). The GEH values for the off-peak and morning peak are 1.6 and 3.6 respectively, both are below the acceptable threshold of 5. These calibrated traffic flows and demand were then fed into the DRACULA models of East Leeds.

Insert Table 2 here
Insert Fig. 3 here

DRACULA simulation models of the base scenarios for the morning and off-peak periods were built and calibrated with the link free-flow speeds and average journey times obtained from floating-car observations. The observed link free-flow speeds were used as inputs to the model. The observed average journey times were used to compare with the simulated journey times. The results suggest that the simulated journey times agree very well with those observed, with a correlation coefficient of 0.992 and 0.970 for the off-peak and morning-peak journey times respectively. Figure 4 shows the observed and simulated journey times for the morning peak and off-peak periods.

Insert Fig. 4 here

5.2 Simulation results and data analysis

The ISA penetration rate was introduced as a control variable. Simulations for both the morning and off-peak time periods were carried out with 10 penetration rates at 10% interval: e.g. 10%, 20%, …100% of the total number of vehicles were equipped with ISA. The results were compared with the base case where there was no mandatory speed control. ISA speed control was evaluated against the following measures of effectiveness (MOE):

a. Network total travel time;
b. Fuel consumption;
c. Total emissions for pollutants CO, NOx, and HC; and
d. Total vehicle-hours spent over a range of speeds (at 5km/hr intervals) for each of the speed limit zones.

For each scenario, the model was run 10 times with different random number seeds to establish a distribution of the output results. The averages over the 10 runs and the 90% confidence interval (C.I.) are derived for network total travel time, fuel consumption and emissions. The results are presented in Tables 4 and 5, and displayed in Figures 5 and 6.

Initial study suggested that the MOE on travel time, fuel consumption and emissions either follow a linear relationship or do not change with ISA penetration. To test the relationship of the MOEs with ISA penetration rates, the results of the 10 simulation runs for the total of 11 scenarios were taken as a single database, which was then analysed using a linear regression model:

$$Y = Y_0 + \alpha \times P \tag{8}$$

where Y is the MOE and P the ISA penetration rate measured as percentages (e.g. 10%). The intercept (Y_0) and the coefficient (α) are parameters to be estimated. The percentage rate of change in MOE with ISA penetration can then be derived as:

$$\beta = \alpha / Y_0 \times 100 \tag{9}$$

which gives the maximum benefit or dis-benefit of ISA on the MOE.

The P-value statistics is used for testing the slope (e.g. the coefficient) being zero: a P-value greater than 0.05 indicates a zero slope whilst a very small P-value (e.g. less than 0.02) indicates that the slope is significant. Results from the regression analysis of the data sample on network travel time, fuel consumption and emissions are presented in Table 6. Discussion of the effect of ISA on each of the MOEs is presented in the following sub-sections.

5.2.1 Network total travel time

The total network travel time, measured in vehicle-hours, is the sum of all individual vehicle journey times from their specified origins and destinations. Table 4 provides a summary of the simulated network travel time. Figure 5 presents the travel time distributions with increasing penetration rates of ISA for the two time periods modelled. It can be seen from both Figure 5 and the results of the linear regression analysis (Table 6) that there is a small but significant increase in network total travel time with increasing ISA penetration during the morning peak period. The average rate of increase is 2.4% between zero and full ISA penetration. A higher rate of increase in travel time, 5.5%, is found for the off-peak period.

Insert Table 4 here
Insert Fig. 5 here

The finding that the effect of ISA on network travel time is more significant for the off-peak period than for the morning peak period is interesting. It is possible that, during the morning peak period, there is a lot of delay and queuing experienced on the network. Therefore vehicles will have very little opportunity to exceed speed limits, and consequently there is very little variation in the average vehicle journey duration. During the off peak period however, there are less vehicles on the network allowing vehicles to travel at higher speeds, sometimes exceeding speed limits. With the implementation of ISA, the amount of vehicle-hours exceeding the speed limits would decrease, resulting in longer journey times. Therefore during off peak times increasing penetration levels of ISA tends to increase average journey times, whereas during peak periods, the congestion automatically reduces vehicles speeds, and hence ISA has very little influence on their journey times. This is further confirmed with detailed analysis of speed distributions in Section 5.2.4.

5.2.2 Network total fuel consumption

The effect of speed control on fuel consumption is shown in Figure 6 and the data presented in Tables 4 and 6. The results suggest that the total fuel consumption gradually decreases with increasing penetration levels of ISA equipped vehicles. An 8% and 9% reduction in fuel consumption is achieved for the off-peak and morning peak period respective if the whole fleet of traffic is under ISA control.

Insert Fig. 6 here

The reduction in fuel consumption can be explained by the fact that ISA controls the top speeds of the vehicles, and by doing so, reduces vehicle acceleration and deceleration cycles and keeps the vehicles cruising at slower and constant speeds. The fuel consumption rate (litre/hour) has a strong and positive relationship with vehicle acceleration and cruising speed, i.e. vehicles consume more fuel when in hard acceleration, and when moving at higher speeds (DOT, 1991).

5.2.3 Pollutant emissions

The summary results of the simulated pollutant emission at different ISA penetrations are presented in Table 5. The statistical analysis of the full simulation database is presented in Table 6. The analysis suggests that, in most of the cases, the impact of ISA control on the total emissions is either statistically insignificant or every small (e.g. a mere 1.9% increase in CO emission during the morning peak period). The only significant impact of ISA on emission was the 4.6% increase in HC emission during the off-peak period.

Insert Tables 5 and 6 here

Generally, emission rates decrease with higher cruising speeds. Opposing this, acceleration and deceleration cycles cause proportionally larger amount of pollutants to be emitted. Without ISA control, vehicles will accelerate and decelerate for longer periods to achieve higher cruising speeds. With ISA control, vehicles will accelerate and decelerate less, and will have lower cruising speeds. Therefore the acceleration and deceleration cycles are accountable for lower emissions, but the lower cruising speed is accountable for proportionally more. Consequently, these two variables counter each other, resulting in little variation of total vehicle emission rates with increasing levels of ISA penetration.

It should be noted that engine technology and emission control devices have advanced significantly during the last decade, with modern petrol fuelled vehicles only emitting significant quantities of CO, NOx and HC during cold starts, acceleration modes and high speed operation (Beebe et al, 2003). Up to date modal emission factor databases for integration with microscopic traffic models are scarce, and when fully developed and released already tend to be slightly dated. These discussions relating to the potential impact of ISA with respect to emissions, should consider that the QUARTET (1992) modal emission factor database used in this study clearly does not reflect the current vehicle fleet characteristics, and hence emissions.

5.2.4 Speed distributions

To establish how ISA equipped vehicles effect the speed distributions on urban road networks, the time each vehicle spent in a specific speed band was recorded. The speeds recorded ranged from 0 to 100 km/hr and were divided into 5 km/hr bands. This allowed the total speed distribution for each level of penetration to be analysed.

Figure 7 compares the speed distributions on all the roads under 30 mph speed limit with zero and 100% ISA control. In order to show more clearly the differences in speed distributions, line charts as opposed to bar charts are used. The points in Figure 7 show the travel time measurements at the top end of the speed bands. Hence the travel time shown at point 50 km/hr refers to the total vehicle-hours spent travelling at speeds between 45 and 50 km/hr. Similarly, where the 100% penetration rate is shown to decline gradually between 55 km/hr and 50 km/hr, this should be interpreted such that no vehicles exceed 50 km/hr.

Insert Fig. 7 here

As expected, the mandatory ISA control effectively reduced the travel times over the speed limit, in this case 30 mph. The reduction as a percentage of the total travel times is calculated and shown in Figure 7 by the shaded areas. For the off-peak scenario, the reduction is 34% between 0% and 100% ISA control. During the morning peak period, however, there is only 20% of the total vehicle-hours exceeding the speed limit. This again suggests that ISA is more effective in the less congested than in heavily congested traffic conditions. In the congested situation, speeds of traffic are largely self-regulated by the congestion.

At speeds below the speed limit, ISA is shown to have minimal effect. The travel times between 0% and 100% ISA at speeds below 50 km/hr are closely matched, especially for the morning peak period.

By reducing the travel times at speeds exceeding the speed limit, hence reducing the variations in high travel speeds (e.g. speeds at and above 50 km/hr), the mandatory ISA has significantly modified the shape of speed distributions. Studies have shown that accident risk is strongly related to the shape of the speed distribution. There is considerable evidence to suggest that drivers who travel either excessively faster or slower than the mean have higher accident liabilities (e.g. Finch, et al., 1994). It can therefore be inferred that mandatory ISA can help improving driver safety.

Similar results can be seen from speed distributions on all roads with 40 mph speed limit (Figures 8), where 16% of total vehicle-hours exceeded the speed limit in the off-peak period, compared to only 12% in the morning peak period. The shapes of the speed distributions at speed higher than 60 km/hr have been significantly transformed with reduced speed variation with full ISA control.

Insert Fig. 8 here

We now examine the speed distributions over the full range of ISA penetrations simulated. Figures 9 and 10 show the distribution of total vehicle-hours on a speed – ISA penetration plane for the off-peak and peak periods respectively. The x-axis of the graphs shows the speeds of traffic in 5 km/hr bands, and the y-axis the total vehicle-hours in each speed band. Along the third axis is the level of ISA penetration. The results are for the whole networks including roads of all speed limits.

Travel times at speeds below the lower speed limit (30 mph or 48 km/hr) do not vary significantly with ISA penetration, especially during the morning peak period (Fig. 10). At the two main speed limits, 30 mph and 40 mph (or 64 km/hr), the 3-D bar graphs clearly show an increase in travel time with increasing ISA penetration.

To illustrate the results more clearly, travel times at individual speed bands for speeds at and higher than 50 km/hr are shown against ISA penetration rates in Figure 11. The travel times at the two speed limits (50 and 65 km/hr) increase significantly with increasing ISA penetration, in between the two speed limits (at 55 and 60 km/hr) and above the higher speed limit (speed greater than 65 km/hr), however, total vehicle hours decrease steadily with ISA penetration.

Another feature worth noting is that, in the morning peak period, there is a high proportion of vehicle-hours spent at speed below 10 km/hr. ISA implementation did not alter the proportion of such congested traffic. This suggests that, though ISA is effective in reducing excessive speeds, it does not induce further slow-moving queues in congested conditions.

Insert Fig. 9 here
Insert Fig. 10 here
Insert Fig. 11 here

5.3 Summary of simulation results

The general findings were:

1) In the morning peak period, traffic speeds were limited largely by congestion. There was therefore either no or very small changes in network total travel time, average speed and emissions under the speed control systems;

2) During the off-peak period, however, there was substantial amount of travel speed exceeding the regulated speed limits. With the implementation of ISA, these high speeds were limited, leading to a significant reduction in average speed, therefore increasing travel times, with increasing speed control penetration rates;

3) In both cases, the speed distributions at lower speeds had not changed significantly. This indicated that speed controls had not induced additional queuing traffic;

4) Speed variation was reduced as a result of the reduction of the fast-moving proportion of traffic. This should help to reduce interactions and potential conflicts between vehicles, which in turn could reduce the frequency of accidents;

5) During both peak and off-peak periods, fuel consumption decreased significantly with increasing penetration rates. This could be caused by reduced acceleration and deceleration cycles, and lower cruising speeds for the ISA vehicles, as fuel consumption has a strong, positive relationship with vehicle acceleration and deceleration;

6) However, there were no significant variations found in total emissions of CO, NOx and HCs with the increasing levels of ISA penetration. Further analysis is required to investigate the impact of ISA on emission with a more rigorous, comprehensive and up to date modal emission factor database, such as Barth et al (2000).

6. Conclusions and Further Research

This paper describes the methodology developed for modelling a new form of speed management: Intelligent Speed Adaptation. The development was made under the general framework of the DRACULA microscopic traffic simulation model. The model was enhanced to explicitly represent the complex interaction between ISA controlled vehicles and other traffic and the control impacts on driver behaviour, network congestion and pollution.

Simulation experiments of a variable mandatory ISA system were conducted in an urban network. Traffic conditions at both the morning peak and the off-peak periods were simulated. The results suggest that the speed control is more effective in less-congested traffic conditions than in severe congestion. Whilst ISA reduces excessive traffic speeds across the network, it does not induce further travel times at low speeds. ISA reduces variation in speed, which in turn should potentially reduce accident numbers and severity. Finally, ISA helps to reduce fuel consumption and so is beneficial to the environment.

This is the first and, to our best knowledge, the only network-wide analysis of ISA impacts. Most of the earlier studies were either conducted through laboratory driving simulator experiments or on-road trials. Other simulation modelling studies are based on a simple corridor (e.g. Hoogendoorn & Minderhoud, 2002), which lacks a proper examination of the complex traffic interaction exhibited in real networks (such as junction interactions and blocking back).

Most of our findings conform to other laboratory, field trial and simulation studies. However, we found an insignificant impact of ISA on pollutant emissions. This is contrary to practical test results from Sweden (Martin, 2002) which found a positive reduction in emissions. The field-test results were based on the engine emissions of modern petrol fuelled vehicles, whilst the modal emission model used in the study was based on the 1980s engine emissions. It is possible that the emission characteristics used in the two studies are very different. Further investigation is to be conducted to try to eliminate the effect of modal emission factors with a more comprehensive and up to date emission database.

In a separate study, simulation analysis of ISA on a rural two-lane road has also been conducted (Liu et al, 1999). A 60 mph speed limit was imposed on ISA vehicles. In general, the ISA effect on network performance was found to be less significant compared to that in the urban environment. The most significant effect of ISA is the reduction in the number of overtaking manoeuvres, which were found to be reduced by up to 10%. Unlike in the case of urban networks, the maximum effect of ISA is reached with a 60% penetration rate.

A further step in the research is to incorporate studies from the driving simulator experiments and the on-road trials, particularly in terms of driver adaptational behaviour under speed control. Another interesting extension to the research is to incorporate signal optimisation with ISA. As the speed control reduces speed variation and produces better vehicle platooning, a greater benefit may be expected. The study presented here is limited to UK traffic conditions and driving behaviour. A research programme has started in a large European consortium to further enhance the modelling methodology described here and to test it on four other European city networks.

REFERENCES

Alkim, T., Schuurman, H. and Tampere, C. (2000) Effect of external cruise and co-operative following on highway: an analysis with the MIXIC traffic simulation model. *Proc. of the 2000 Intelligent Vehicle Conference.*

Almquist, S., Hyden, C. & Risser, R. (1991) Use of speed limiters in cars for increased safety and a better environment. *Transport Research Record,* **1318**, 34-39.

Almquist, S. and Nygård, M. (1997) Dynamic speed adaptation. Field trial with automatic speed

adaptation in urban area. Bulletin 154. Lund University, Sweden.
Anderson, R.W.G., McLean, A.J., Farmer, M.J.B, Lee, B.H. and Brooks, C.G. (1995) Vehicle travel speeds and the incidence of fatal pedestrian crashes. *International Research Conference on the Biomecanics of Impact,* 13-15 September IRCOBI Cong. 1995.
Andre, M. and Pronello, C. 1997, Relative influence of acceleration and speed on emissions under actual driving conditions. Int. Journal of Vehicle Design, Vol 18, Nos 3/4 (Special Issue), 1997.
Barbosa, H.M, Tight, M.R. and May, A.D. (2000) A model of speed profiles for traffic calmed roads. *Transportation Research,* **34A**, 103-123.
Barth, M., An, F., Younglove, T., Scora, G., Levine, C., Ross, M. and Wenzel, T. (2000) Comprehensive Modal Emission Model. *User Guide, University of California, Riverside Center for Environmental Research and Technology,* 3rd January 2000.
Beebe, J., Bell, M.C. and Tate, J.E. (2003) Analysis of modal emissions – implications for air quality modelling and management. Paper presented at the *4th University Air Quality Conference*, Prague, March 2003.
Carsten, O. and Comte, S.L. (1997) UK work on automatic speed control. In Proceedings of ICTCT 97 Conference, November 1997, Lund, Sweden.
Comte, S.L. (2000). New Systems, new behaviour? *Transportation Research*, **3F**, 95-111.
Comte, S.L., Wardman M. and Whelan, G. (2000). Public acceptance of speed limiters for private car use: implications for policy and implementation. *Transport Policy*, **7**, 259-267.
Dahlstedt, S. (1994) The SARTRE-tables. Opinions about traffic and traffic safety of some European cities. VTI Report No 403/403A, Linköping, Sweden.
DoT (1991) *New car fuel consumption: the official figures December 1991*, Department of Transport, UK.
Ferreira, LJA. (1982) Car fuel consumption in urban traffic, the results of a survey in Leeds using instrumented vehicles. ITS Working Paper 162, Institute for Transport Studies, University of Leeds.
Finch, D.J., Kompfner, P., Lockwood, C.R. and Maycock, G. (1994) *Speed, Speed Limits and Accidents*. Project Report 58. Transport Research Laboratory, Crowthorne, UK.
Garber, N.J. and Gadirau, R. (1988) *Speed variance and its influence on accidents.* AAA Foundation for Traffic Safety, Washington DC, USA.
Gipps, PG (1981) A behavioural car-following model for computer simulation. *Transportation Research*, **15B**, 105-111.
Hauer, E. (1971) Accidents, overtaking and speed control. *Accident Analysis and Prevention,* **3**, 1-13.
Hodge, A. R. (1992) A Review of the 20 mile/h speed zones: 1991. *Traffic Engineering & Control*, **33**(10), 545-547.
Hoogendoorn, S.P. and Minderhoud, M.M. (2002) Motorway flow quality impacts of advanced driver support systems. Paper presented at 81st Transportation Research Board Annual Conference, Washington.
Kulmala, R. (1996) Traffic safety and transport telematics. In *Proc. of the Conference on Road Safety in Europe*, 9-11 September 1996, Birmingham.
Lind, G. (1999) Large-scale testing of intelligent speed adaptation – important evaluation issues. Proc. *AET European Transport Conference, Seminar D,* 91-103, Cambridge.
Liu, R. (2003) The DRACULA microscopic traffic simulation model. To appear in *Transport Simulation* (eds. Kitamura, R., Kuwahara, M. and Schreckenberg, M.), Springer.
Liu, R. Tate, J. and Boddy R. (1999) *Simulation Modelling on the Network Effects of EVSC Systems*, Deliverable 11.3, External Vehicle Speed Control, Department of the Environment, Transport and the Region, UK.
Liu R., Van Vliet D., and Watling D. P. (1995) DRACULA: Dynamic Route Assignment Combining User Learning and microsimulAtion. Proc. *PTRC European Transport Forum, Seminar E,* 143-

152.
Martin, J. (2002) After a 4 year trial – what the Swedes think of ISA. *Traffic Engineering & Control*, **43**(10), 376-379.
Munden, J.M. (1967) *The relationship between a driver's speed and his accident rate.* TRRL Report LR 88, Transport and Road Research Laboratory, Crowthorne, UK.
Pasanen, R. and Salmivaara, H. (1993) Driving speeds and pedestrian safety in the City of Helsinki. *Traffic Engineering & Control,* **34**(6), 308-310.
QUARTET (1992) Assessment of current tools for environment assessment in QUARTET, DRIVE II Project V2018: QUARTET, September 1992.
Salusjärvi, M. (1981) The speed limit experiments on public roads in Finland. Technical Research Centre of Finland. Publication 7/1981. Espoo, Finland.
Van Vliet, D. (1982) SATURN - a modern assignment model. *Traffic Engineering & Control*, **23**(12), 578-581.
Van Vliet, D. (2002) *SATURN 10.2 User Manual*, Institute for Transport Studies, University of Leeds.
Várhelyi, A. (1996) *Dynamic Speed Adaptation Based on Information technology – a Theoretical Background.* Ph.D. Thesis, Lund University, Sweden.
Várhelyi, A. and Mäkinen, T. (2001) The effects of in-car speed limiters: field studies. *Transportation Research*, **9C**, 191-211.
Webb, P.J. (1980) *The effect of an advisory speed signal on motorway traffic speeds.* TRRL Supplementary Report SR615, Transport and Road Research Laboratory, Crowthorne, UK.
West, L.B.Jr and Dunn, J.W. (1971) Accidents, speed deviation and speed limits. *Traffic Engineering,* **11**(41), Washington DC, USA.

About the authors

Ronghui Liu is a Senior Research Fellow at the Institute for Transport Studies, University of Leeds. She is instrumental in the development of the state-of-art dynamic network microsimulation model DRACULA, taking charge of both the modelling methodology and the detailed programming of the model. She has established an international reputation as one of the leading researchers in network simulation modelling and has built a strong research and development team focusing on the development of modelling tools for evaluating the impact of advanced technology and dynamic traffic management strategies on transport and environmental systems.

James Tate is a research fellow at the Institute for Transport Studies. His principal research interests include traffic and air quality monitoring, modelling and management. His research is focussed upon urban areas, integrating monitoring and modelling tools, to develop and implement management strategies to improve congestion and environmental impacts. With respect to microsimulation modelling using the DRACULA software, James has assessed the potential impact of Intelligent Speed Adaptation, public transport priority schemes, signal control and queue relocation policies.

Table 1. Fuel consumption rates vs. cruising speeds

Speed (kph)	10	20	30	40	50	60	70	80	90	100	110	120
Rate (ml/sec)	0.26	0.29	0.34	0.40	0.48	0.59	0.74	0.92	1.15	1.43	1.77	2.17

Table 2. Comparison of modelled and observed flows for the off-peak period.

Site	Direction	Observed flows	Modelled flows
A	W to E	1640	1622
	E to W	1491	1554
B	W to E	1946	2118
	E to W	2246	2134
C	W to E	2261	2201
	E to W	2027	2067
D	W to E	755	758
	E to W	964	854
E	W to E	912	1007
	E to W	1045	1037
F	S to N	655	661
	N to S	594	592
G	S to N	635	719
	N to S	774	783

Table 3. Comparison of modelled and observed flows for the morning peak period.

Site	Direction	Observed flows	Modelled flows
A	W to E	1840	1818
	E to W	2653	2750
B	W to E	1885	2004
	E to W	2956	2563
C	W to E	2252	2184
	E to W	2865	2537
D	W to E	1869	1510
	E to W	584	561
E	W to E	1042	1132
	E to W	1491	1767
F	S to N	756	615
	N to S	746	716
G	S to N	751	749
	N to S	1433	1603

Table 4. Simulation results of the impacts of ISA on network total travel time and fuel consumption. The means and 90% confidence interval (C.I.) over the 10 simulation runs are presented for both the morning and off-peak scenarios.

ISA penetration rate (%)	Total travel time (vehicle-hours)				Fuel consumption (litres)			
	AM-peak		Off-peak		AM-peak		Off-peak	
	Mean	90% C.I.	Mean	90% C.I.	Mean	90% C.I.	Mean	90% C.I.
0	407.4	5.8	281.9	3.0	7128	37	4959	32
10	406.7	3.4	282.1	2.9	7242	42	4962	25
20	407.3	4.7	283.6	11.0	7222	44	4927	56
30	409.6	5.7	284.6	6.1	7195	51	4922	50
40	405.8	5.7	289.2	11.8	7084	45	4885	68
50	408.3	10.0	293.2	14.6	7009	90	4863	82
60	407.6	5.2	293.3	11.5	6894	44	4815	74
70	415.2	5.5	292.3	10.0	6863	48	4742	165
80	412.7	7.4	299.2	17.8	6730	68	4725	108
90	413.2	6.7	297.8	18.3	6637	60	4636	111
100	418.0	5.4	299.9	10.8	6554	42	4540	42

Table 5. Simulation results of the impacts of ISA on total network emissions from pollutants CO, NOx and HC for the off-peak period (a) and the morning-peak period (b). The means and 90% confident interval over 10 simulation runs are presented.

(a) Off-Peak

ISA penetration rate (%)	CO Emission (kg)		NOx Emission (kg)		HC Emission (kg)	
	Mean	90% C.I.	Mean	90% C.I.	Mean	90% C.I.
0	701	19	19.1	0.5	49.3	1.0
10	691	10	18.7	0.3	48.7	0.6
20	691	38	18.6	0.9	48.7	2.2
30	693	24	18.6	0.6	48.8	1.3
40	707	45	19.0	1.1	49.7	2.5
50	697	40	19.2	1.3	50.4	3.0
60	717	44	19.3	1.1	50.5	2.5
70	721	10	19.4	0.9	50.8	1.6
80	730	56	19.7	1.3	51.7	3.5
90	723	69	19.7	1.7	51.3	3.9
100	702	25	19.3	0.6	50.3	1.4

(b) AM-Peak

ISA penetration rate (%)	CO Emission (kg)		NOx Emission (kg)		HC Emission (kg)	
	Mean	90% C.I.	Mean	90% C.I.	Mean	90% C.I.
0	1301	24	34.4	0.6	86.2	1.4
10	1320	24	34.6	0.6	86.7	1.3
20	1312	16	34.3	0.4	86.3	1.0
30	1316	23	34.4	0.6	86.6	1.4
40	1296	23	33.9	0.6	85.5	1.2
50	1300	37	33.9	1.0	85.8	2.3
60	1282	21	33.6	0.5	85.3	1.2
70	1308	25	34.4	0.7	87.0	1.4
80	1290	31	34.0	0.8	86.3	1.8
90	1291	27	34.0	0.9	86.2	1.8
100	1289	30	34.3	0.8	87.0	1.6

Table 6. Results of the linear regression analysis of the effect of ISA penetration rate on network total travel time, fuel consumption, and emission from pollutant CO, NO_X and HC. The percentage rate of change (β) is only given for those with a P-value less than 0.05.

MOE	Time period	Intercept (Y_0)	Coefficient (α)	P-value	Percentage change (β)
Total travel time (veh-hrs)	AM-peak	405.2	9.8	0.0036	2.4
	Off-peak	280.7	15.5	0.0011	5.5
Fuel consumption (litre)	AM-peak	7298.8	-682.0	2.79E-43	-9.3
	Off-peak	5013.6	-408.0	7.08E-27	-8.1
CO emission (kg)	AM-peak	1313.0	-24.5	0.018	-1.9
	Off-peak	692.5	21.5	0.157	-
NOx emission (kg)	AM-peak	34.35	-0.35	0.188	-
	Off-peak	18.66	0.76	0.050	-
HC emission (kg)	AM-peak	86.16	0.26	0.713	-
	Off-peak	48.7	2.25	0.014	4.6

Figure Captions:

Figure 1. ISA speed limit distribution on the east Leeds network.

*Figure 2.*Data collection points in the east Leeds network.

*Figure 3.*Comparison of modelled and observed flows for (a) off-peak and (b) morning peak periods.

Figure 4. Journey time comparison for (a) off-peak and (b) morning peak periods.

Figure 5. Distributions of network total travel times with ISA penetration rates for the morning (am) peak and the off peak period. The points show the average travel times over the 10 simulation runs with different random number seeds: diamonds are for the morning peak and squares for the off-peak period. The error bars show the 90% confidence intervals of the means. The lines and equations show the results of a linear fitting to the simulated data.

Figure 6. Distribution of fuel consumption with ISA penetration rates for the two time periods. Symbols are as in Fig. 5.

Figure 7. Speed distributions without and with 100% ISA control on all 30 mph road sections for (a) off-peak and (b) peak periods. The x-axis shows the speeds of traffic in 5 km/hr bands and y-axis the total vehicle-hours in each speed band. The dashed line is for the base case where no ISA-controlled vehicles were simulated, whilst the solid line represents the situation with full 100% ISA penetration. The shaded areas under the 0% ISA lines represent the total vehicle-hours at speeds exceeding the speed limit; their percentage to the total travel times are indicated by the numbers shown.

Figure 8. Speed distributions without and with 100% ISA control on all 40 mph road sections for (a) off-peak and (b) peak periods.

Figure 9. Distribution of total travel times of the off-peak period on a speed - ISA penetration plan. The speeds in 5 km/hr band-width are displayed along the horizontal axis, ISA penetration rates (%) along line-of-sight, and the total vehicle-hours spent in each cell of speed band – penetration rate are displayed along the vertical axis.

Figure 10. Distribution of travel time over the full rage of speeds – ISA penetration rates for the morning peak period.

Figure 11. Distributions of travel times with ISA penetration rates for individual speed bands for (a) the off peak and (b) the morning peak period respectively. The lines associated with the two main speed limits, 30 mph and 40 mph, are marked.

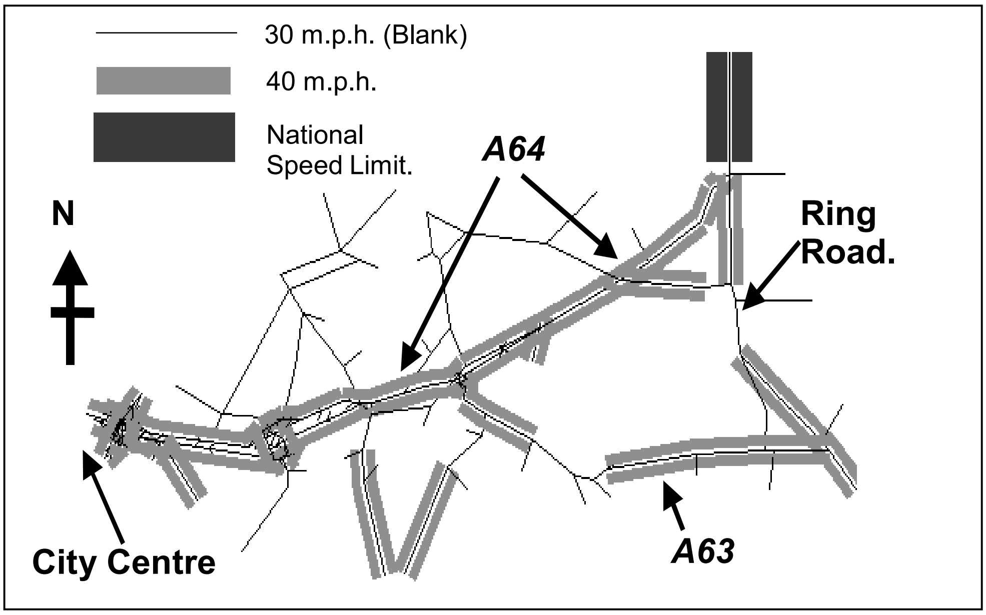


Figure 1. ISA speed limit distribution on the east Leeds network.

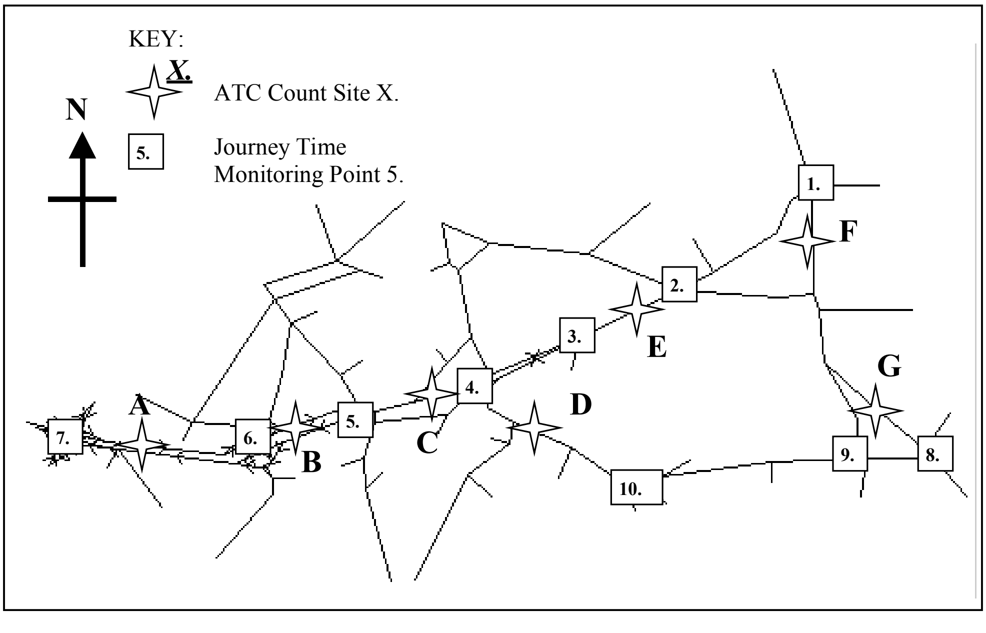
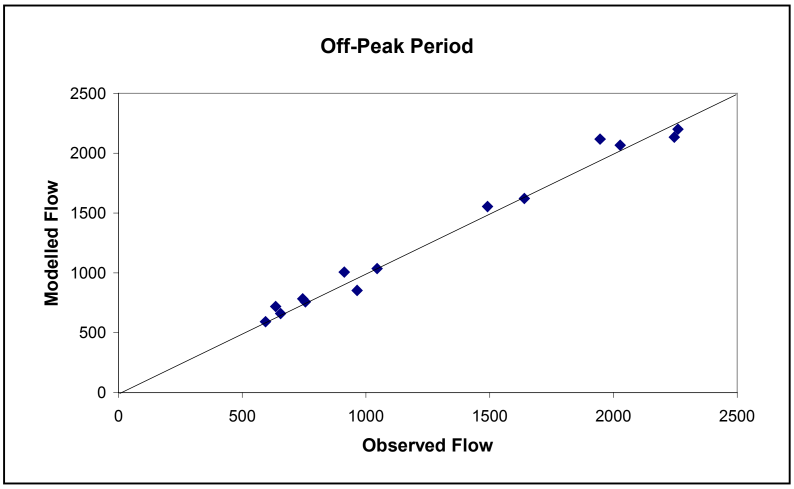


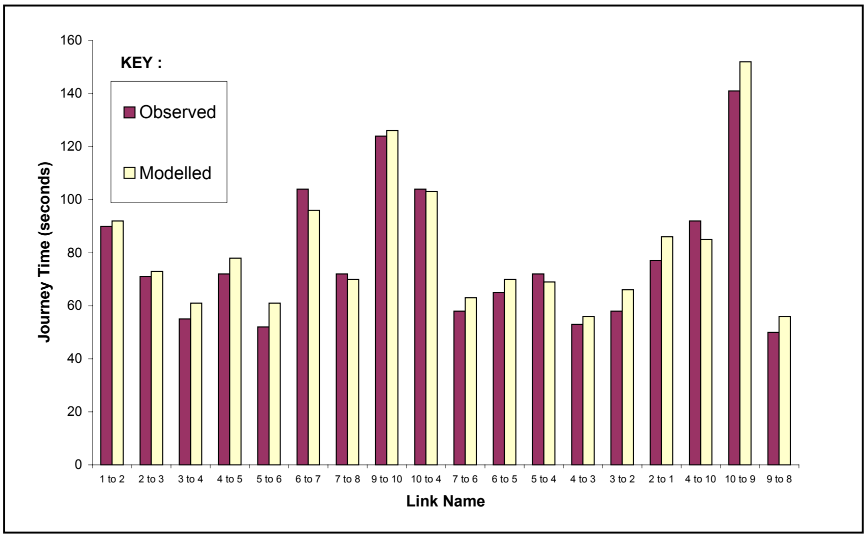
*Figure 2.*Data collection points in the east Leeds network.



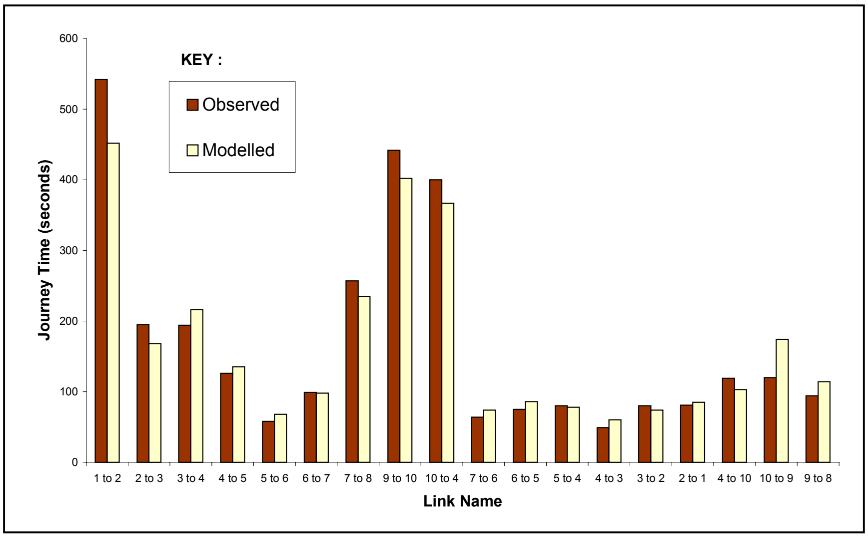
(a)

(b)

*Figure 3.*Comparison of modelled and observed flows for (a) off-peak and (b) morning peak periods.



(a)



(b)

Figure 4. Journey time comparison for (a) off-peak and (b) morning peak periods.

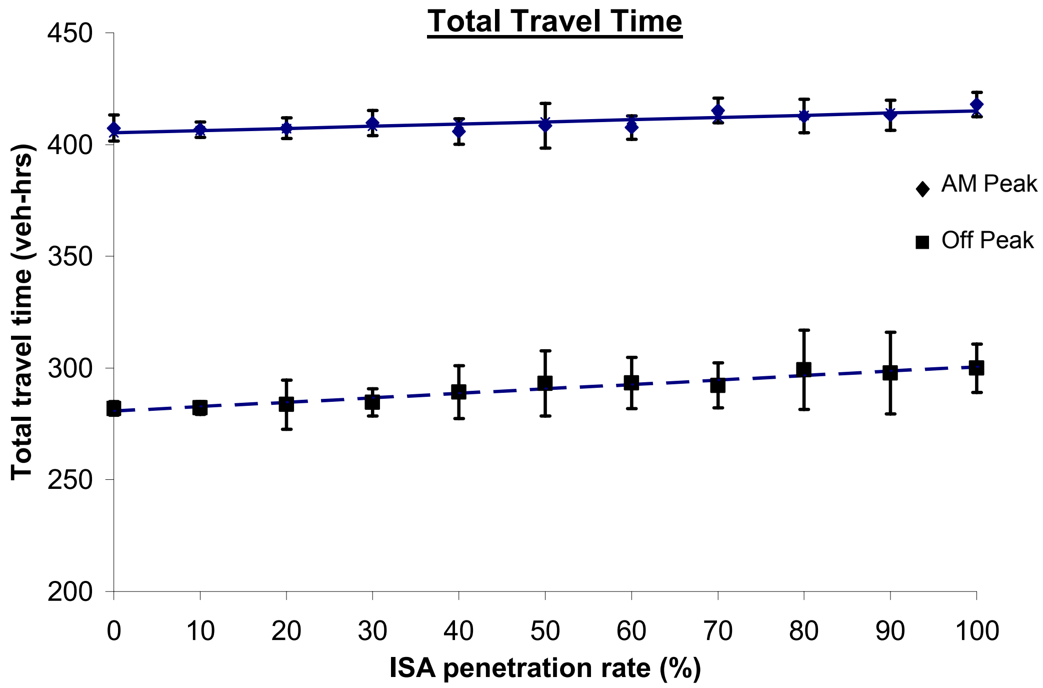


Figure 5. Distributions of network total travel times with ISA penetration rates for the morning (am) peak and the off peak period. The points show the average travel times over the 10 simulation runs with different random number seeds: diamonds are for the morning peak and squares for the off-peak period. The error bars show the 90% confidence intervals of the means. The lines show the results of a linear fitting to the simulated data.

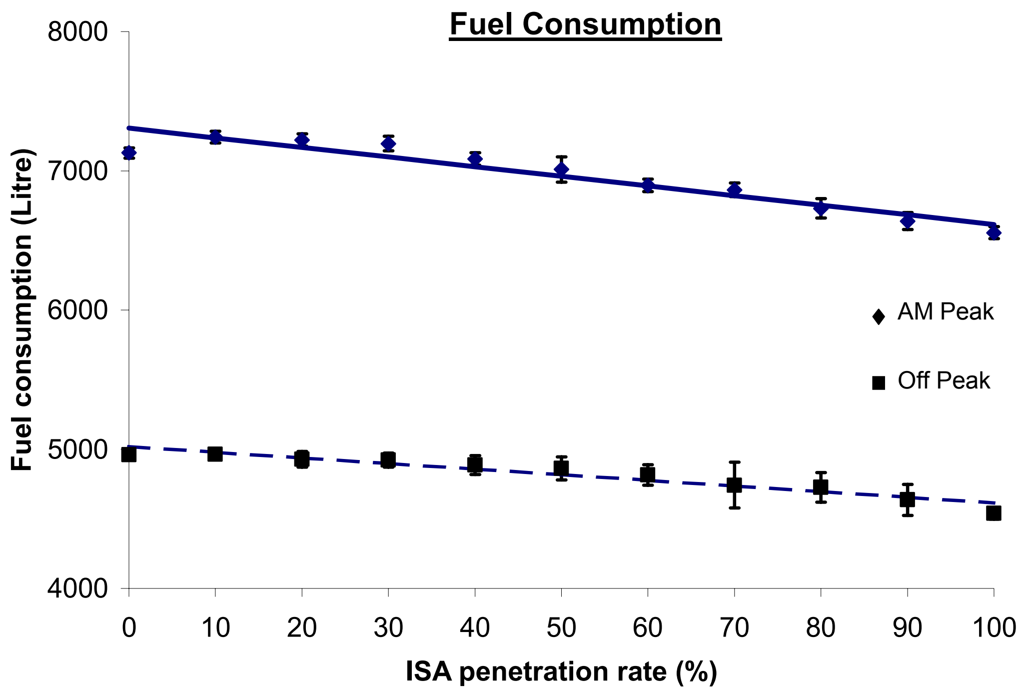
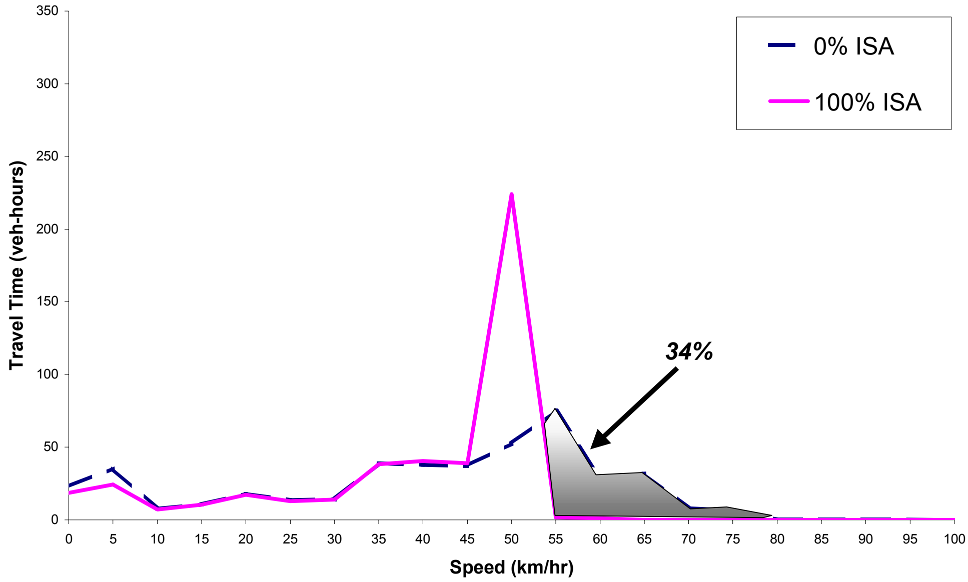
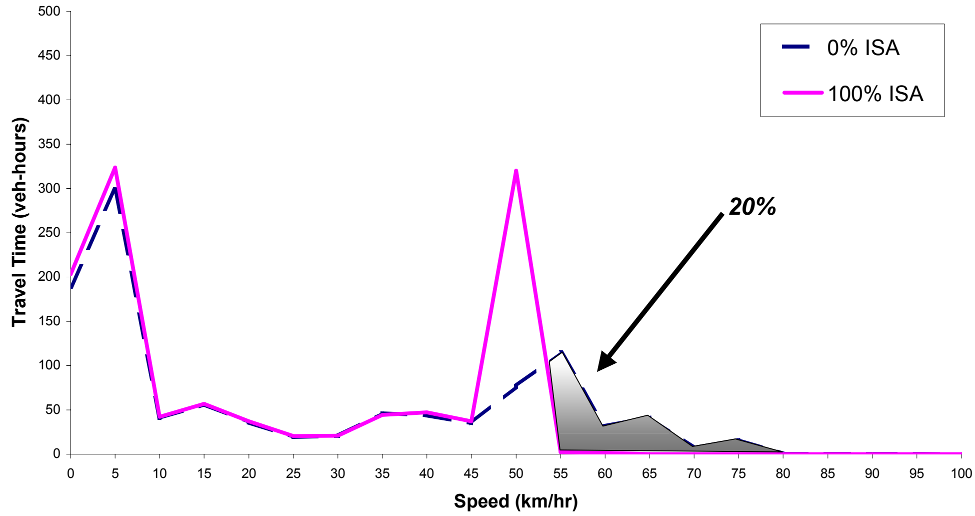


Figure 6. Distribution of fuel consumption with ISA penetration rates for the two time periods. Symbols are as in Fig. 5.

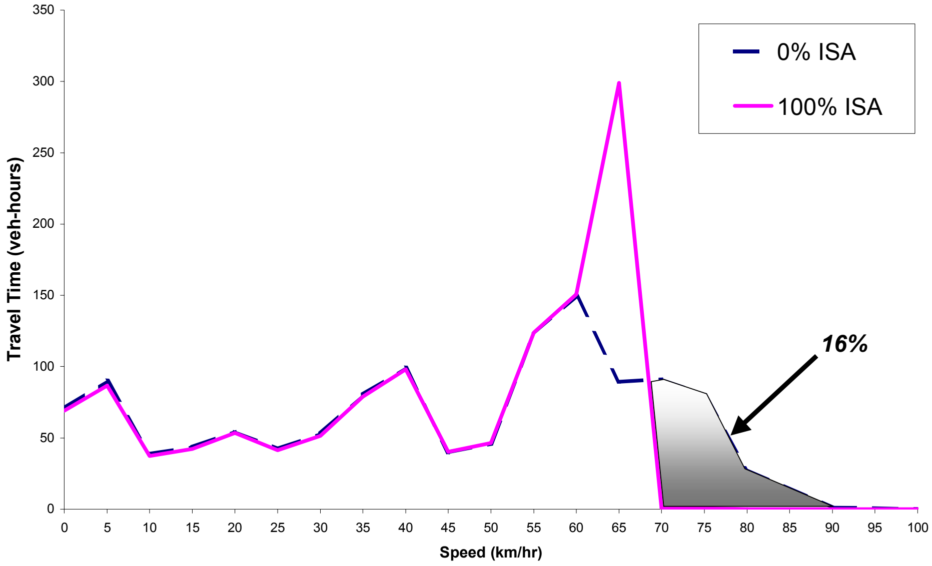


(a)

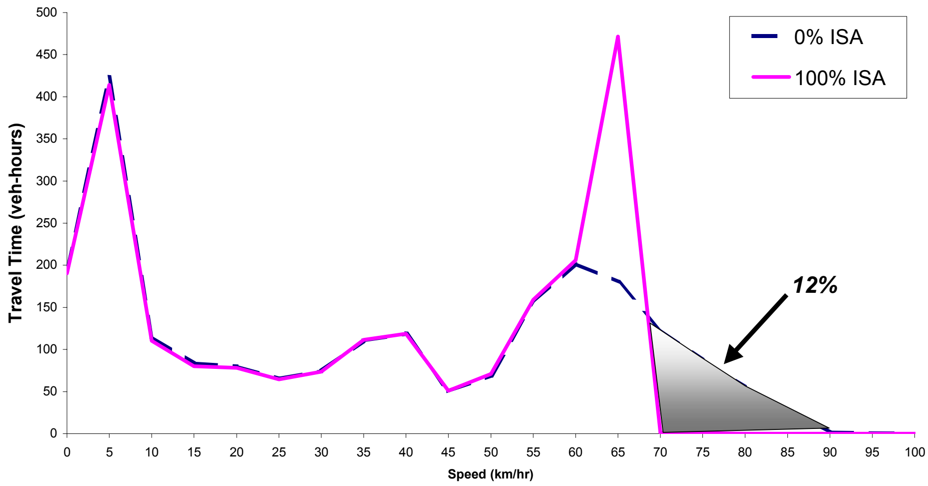


(b)

Figure 7. Speed distributions without and with 100% ISA control on all 30 mph road sections for (a) off-peak and (b) peak periods. The x-axis shows the speeds of traffic in 5 km/hr bands and y-axis the total vehicle-hours in each speed band. The dashed line is for the base case where no ISA-controlled vehicles were simulated, whilst the solid line represents the situation with full 100% ISA penetration. The shaded areas under the 0% ISA lines represent the total vehicle-hours at speeds exceeding the speed limit; their percentage to the total travel times are indicated by the numbers shown.



(a)



(b)

Figure 8. Speed distributions without and with 100% ISA control on all 40 mph road sections for (a) off-peak and (b) peak periods.

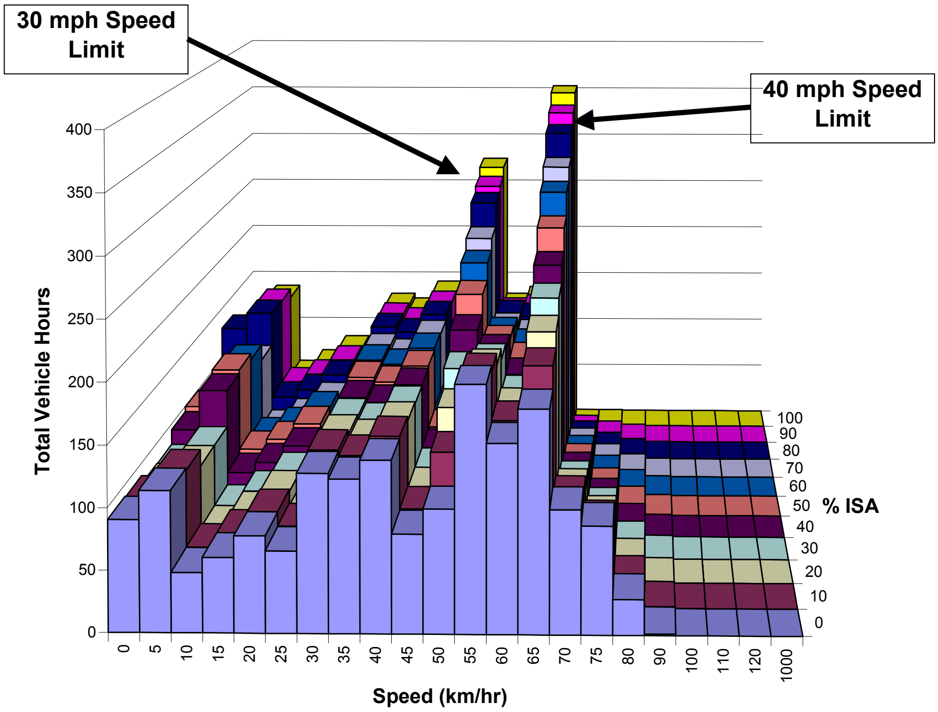


Figure 9. Distribution of total travel times of the off-peak period on a speed - ISA penetration plan. The speeds in 5 km/hr band-width are displayed along the horizontal axis, ISA penetration rates (%) along line-of-sight, and the total vehicle-hours spent in each cell of speed band – penetration rate are displayed along the vertical axis. The bands within which the two main speed limits (e.g. 30 and 40 mph) fall are highlighted.

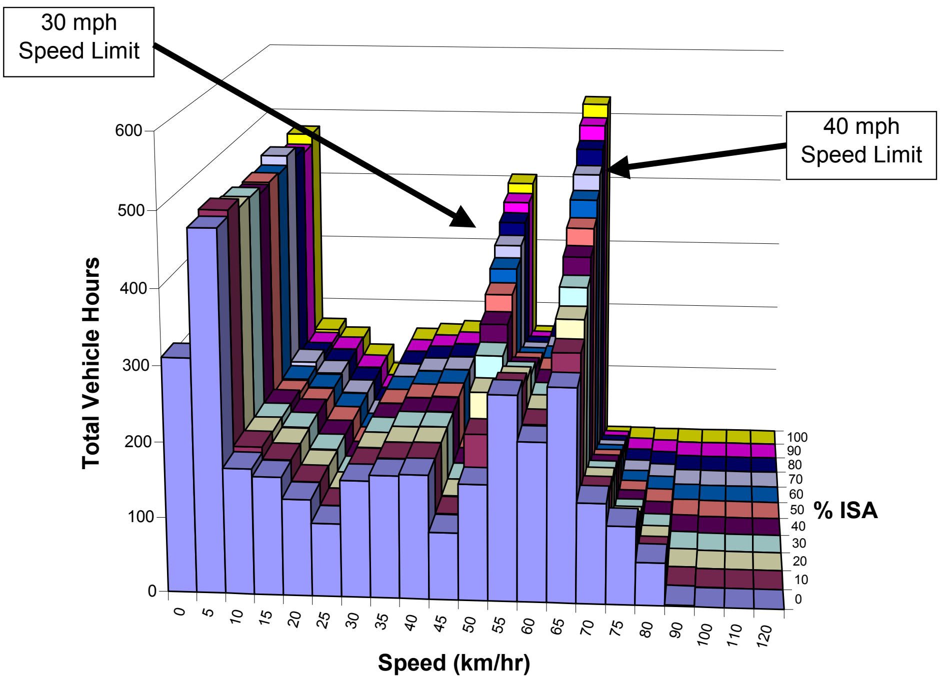
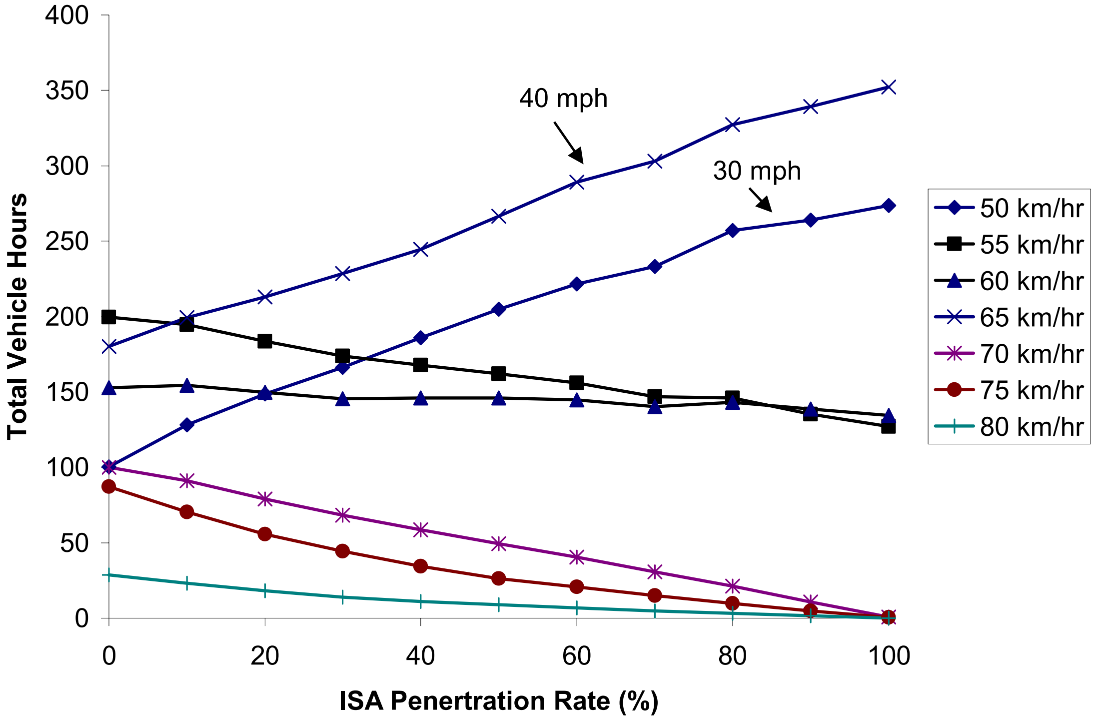
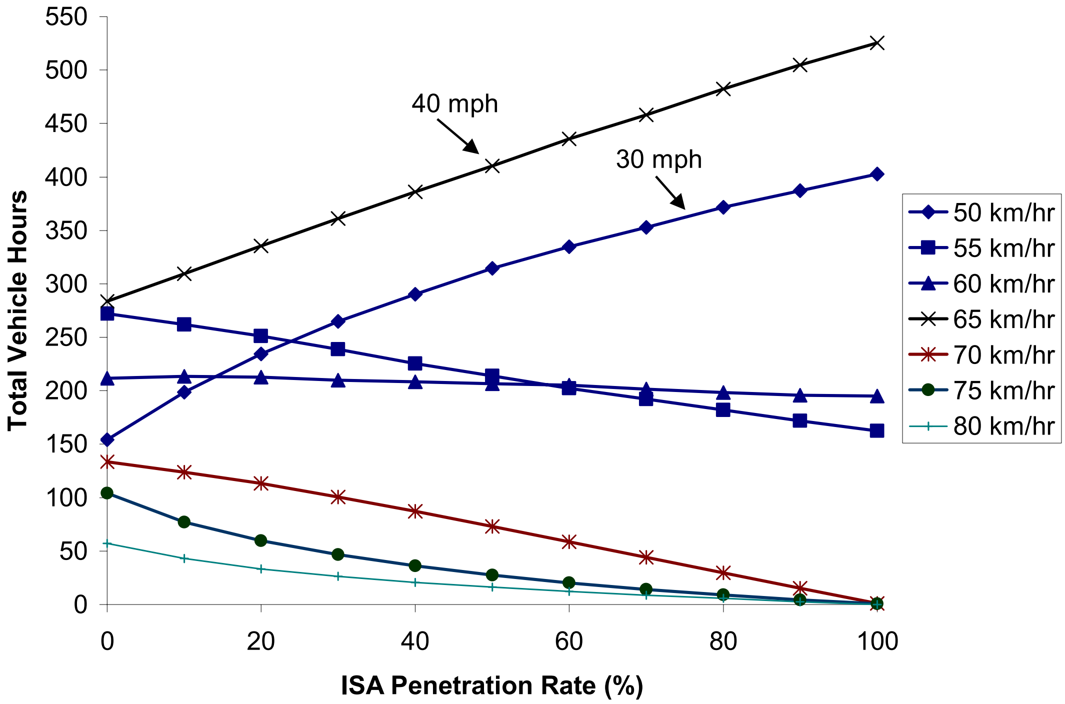


Figure 10. Distribution of travel time over the full rage of speeds – ISA penetration rates for the morning peak period.



(a)



(b)

Figure 11. Distributions of travel times with ISA penetration rates for individual speed bands for (a) the off peak and (b) the morning peak period respectively. The lines associated with the two main speed limits, 30 mph and 40 mph, are marked.