INTERSECTION TRAFFIC CONTROL - QUANTIFYING THE USER COSTS

David C. Biggs,
Research Scientist (Road Transport),
Australian Road Research Board,
Victoria.

Darrell P. Bowyer,
Principal Research Scientist (Road Transport),
Australian Road Research Board,
Victoria.

ABSTRACT: *A number of different forms of traffic control or interesection layouts could be used at a particular intersection. The costs to users of the intersection under the possible control conditions will vary in type and distribution across users. Two of the major direct costs to users are travel time and fuel consumption. Another, less quantifiable, cost to the user is the accident risk. When determining the appropriate form of traffic control at an intersection, maximising intersection efficiency, taking into account all user costs, should be a primary objective. The benefit of a change in traffic control should then be weighed against the costs of implementing and maintaining the scheme. It is therefore necessary to be able to identify the value of each type of user cost under any proposed form of intersection control. Analytical tools, such as the traffic model INSECT, enable delay time and fuel consumption at intersections under different forms of traffic control and intersection layouts to be estimated. The INSECT model is described and its usefulness demonstrated by considering the effect of changes in traffic control or interesection layout at several intersections. The user benefits and the conditions under which they occur are discussed and some general conclusions on the comparative costs of intersection control alternatives are reached.*

INTRODUCTION

The minimisation of the cost of travel to users of the road network is a primary objective of the traffic manager. A major portion of these costs occur because of the intersection of roads within the network. The choice of geometric design and traffic control for an intersection will therefore have a great bearing on the costs to users of the network.

A number of different forms of traffic control could be used at a particular intersection, for example priority control (stop or give-way), roundabout or traffic signals. All these have different costs to the users associated with them. Two of the major direct costs to the users are travel (or delay) time and fuel consumption. Another less quantifiable cost to the user is the accident risk. The cost of air pollution and noise is borne by all people in the vicinity of the intersection. When determining the appropriate form of traffic control at an intersection, maximising intersection efficiency, taking into account all user costs, should be a primary objective.

At present, procedures for determining the appropriate level of control at intersections make use of fairly broad volume and safety 'warrants' to aid the traffic manager (see, for example, Daley (1984)) . The Australian Standard (SAA, 1986) encourages the use of a cost-benefit analysis to determine the appropriate form of control, but the data required for this type of analysis is difficult and expensive to collect. The traffic model, INSECT (Nairn and Partners, 1986), simulates the passage of individual vehicles through an intersection and provides performance estimates which could be used by the traffic manager in determining the appropriate form of control.

In this paper, the user costs are discussed and the model INSECT is described briefly. The usefulness of INSECT is then demonstrated by considering several interesting cases of changes in traffic control and intersection layout. The user benefits from control changes and the conditions under which those benefits occur are discussed and generalised where possible. The two major user costs considered here are delay time and fuel consumption. These benefits must be weighed against the accident risk of the different forms of intersection control.

VALUING TRAVEL COSTS

The cost of travel for users of the road network can be divided up into fixed and variable costs. Fixed costs such as the cost of the vehicle, registration and insurance are incurred independently of the amount of travel and are therefore not considered when comparing the cost of travel under different forms of traffic control. For this purpose variable costs such as travel time and fuel consumption, should be considered.

The major variable cost is that of travel time, or equivalently when comparing traffic control schemes, delay time. The value of travel time has been a topic of much debate. A value of one third of average weekly earnings has been used in many studies, but there is some uncertainty whether small time savings are as valuable, per second, as longer time savings (Lay, 1985). One method of determining the value of travel time is by considering the cruise speed that people choose to travel at when unconstrained by other traffic and road conditions. Travel time can be reduced by increasing travel speed, but at high speeds this results in an increase in fuel consumption and therefore cost. Given a person's desired cruise speed and the fuel consumption-speed relationship for the vehicle, the person's value of travel time can be calculated. Assuming an average, desired, unconstrained cruise speed of 100 km/h, Biggs and Akcelik showed that for a medium sized car this corresponded to 13.5 L/h which, at a petrol cost of $0.58/L, is equivalent to $8.00 per hour. At a cruise speed of 90 km/h the value of travel time is $5.40 per hour. The average value of travel time saved for new small to medium cars for cruise speeds of 100 km/h has been estimated from vehicle data given in Royalauto to be $5.30 per hour. These values are greater than one third of weekly earnings (about $4.30/h). Since the method calculates the value of incremetal time saving, this suggests that the value of small time savings are at least as valuable as large savings. The higher value could be due, in part, to the driver's lack of knowledge of the fuel costs of higher speeds. Note that this method does not include the increased accident risk of travelling at high speeds. Inclusion of this cost would increase the estimated value of travel time.

Another important component of the cost of travel is fuel consumption. The importance of this component has increased greatly in the last decade with increasing fuel prices. The trend to more fuel efficient cars has off-set this to some extent. Fuel consumption is difficult to measure and has therefore been ignored in many studies when evaluating traffic management schemes. However, recent advances in modelling fuel consumption (see for example Bowyer, Akcelik and Biggs, 1985) and the incorporation of fuel consumption models into traffic models enable the effects of changes in traffic control on fuel consumption to estimated accurately. The benefit of fuel savings has been found to be of a similar order of magnitude as the travel time savings for changes in traffic control at some intersections (Bowyer and Biggs, 1986).

The third major component of travel cost can be termed the accident risk. The cost of an accident can be large but the chance of experiencing this cost is small. During any travel there is a chance of an accident and this is a risk that people take in travelling on the road can therefore be thought of as a cost of travel. However, this cost is difficult to measure as accidents occur so infrequently and, as with the value of travel time, the cost of accidents are difficult to quantify. The frequency of accidents appears to be dependent on both exposure and site related features and traffic models have not been able to accurately predict the accident risk. The prediction of accident risk for an intersection under a given form of control and given volume levels is an area for future research. The cost of accident risk is not considered in this paper when comparing user costs of different forms of traffic management.

Other user costs such as tyre and vehicle wear are much less than travel time and fuel consumption costs and are not considered here.

Total user travel costs are calculated by adding the monetary values of travel time and fuel consumption. A value of travel time was taken as $5.00/h and the price of fuel as $0.58/L. These travel costs could then be compared with the monetary estimates of the accident risk when assessing different traffic control schemes.

EVALUATION OF TRAFFIC CONTROL SCHEMES

The two main points to be considered when comparing traffic managements schemes are the overall operational efficiency of the intersection under the various schemes and the cost-benefit ratio for implementing and maintaining the schemes. All significant costs and benefits should be included when calculating these quantities.

Reductions in delay time will usually induce a reduction in fuel consumption, i.e., they are complementary variables. Similarly, reduced fuel consumption will usually be complementary to reduced air pollution and noise levels. However, there will typically be a conflict between reduced fuel and delay cost and increased safety. All quantities must be estimated with a similar degree of accuracy to be included in th analyses.

In practice, other objectives are also considered when choosing the appropriate traffic managements scheme. Equity for all travellers through the intersection might be considered an advantage. In other situations schemes could be altered so that no group of users experience greater costs than some specified maximum. This could be important in congested conditions where users on the minor roads may experience excessively long delays in the most efficient system. However, the specified maximum cost must be chosen carefully so that the reduction in overall intersection efficiency is kept small.

ESTIMATION OF DELAY TIME AND FUEL CONSUMPTION

In the evaluation of traffic control schemes traffic models are the primary means of estimating delay and fuel consumption, especially in the design phase. On-road data are often costly to collect and models can be used for comparing in advance different traffic control schemes and intersection layouts. A hierarchy of traffic models exist covering the range of applications from individual intersections to large urban networks. The two models, INSECT and SIDRA-2 (Akcelik, 1986), are suitable for estimation of the performance of individual intersections. SIDRA-2 is restricted to vehicle actuated (VA) signalised intersections, but with its fast processing time it is ideally suited to the design and specification of signal settings for this type of intersection control.

The simulation model INSECT is suitable for assessing the performance of an individual intersection under stop, give-way, roundabout (one or two-lane) or signal control. For signalised control, the effect of the signal personality (number of phases, right turn arrows, etc.) and timings (e.g. cycle, gap and waste times, etc.) can be tested. In addition, the effect of linking the signals to upstream intersections can be tested. The software used to control the operation of the signals in INSECT is the same as that used by the Department of Main Roads-NSW and the Road Traffic Authority-Victoria in actual operation. Thus INSECT realistically represents signal controllers presently in use and the personalities generated for use in INSECT can then be used directly in the signals controllers on the road.

Given a detailed description of the intersection (e.g. number of lanes, slip lanes, length of turn lanes or hold bays) and traffic volumes on all routes, INSECT simulates the passage of vehicles through an intersection. Variables such as points of conflict and gap times can be specified by the user or default estimates used. A sub-program of INSECT, called CODAID, greatly facilitates the writing of the intersection description file required by INSECT. The signal personality file can be generated using another sub-program, CGEN, but the user will still require a good knowledge of signal control systems. The report output file gives the values of a number of performance variables, including delay and fuel consumption, for each specified time interval. Further details on INSECT are given in Nairn and Partners (1986) and examples and hints on the use of INSECT are given in Biggs and Bowyer (1986)

INSECT has been found to provide a reasonable representation of the operation of individual intersections. The estimated values of delay time and fuel consumption resulting from a change in traffic control have been found to agree well with values measured on the road (Biggs and Bowyer, 1986). Thus, INSECT is a useful tool for assessing different forms of traffic control and intersection layouts.

COMPARISON OF DIFFERENT FORMS OF INTERSECTION CONTROL

A study of the effects of different forms of intersection control on fuel consumption was undertaken at the Australian Road Research Board. The main findings and recommendations are presented in the report by Bowyer and Biggs (1986) with details given in several supplementary reports (Biggs and Murphy (1986), Biggs (1986) and Biggs and Bowyer (1986)). Performance estimates calculated from on-road measurements and simulations using the traffic model INSECT were found for various levels of traffic control at three intersections. Stop, give-way, roundabout and signal control, with several different signal control strategies, were considered. This paper focuses on the benefits to road users of a number of the traffic control schemes considered in the study and the operating conditions under which those benefits occur.

Intersection of Local Collector and Limited Arterial Roads

The intersection depicted in Fig. 1 is typical of many intersections between local collector and limited arterial roads in Melbourne. Under the broad guidelines given in the Australian Standard (SAA, 1986), priority, roundabout or signal control might be appropriate. Due to the delays experienced on Clarinda road and the accident record, priority control was replaced by a roundabout. As discussed in Bowyer and Biggs (1986), this was found to reduce total delay and fuel consumption during the peak period, but during the off-peak period the reduction in delay was small and there was a significant increase in fuel consumption.

The performance of this intersection under priority, roundabout and signal control and under priority control with an alternative layout (shown in Fig. 2) will be considered here in detail. INSECT simulations were run for traffic volumes ranging from 300 to 1000 veh/h on the major road and 100 to 600 veh/h on the minor road (both approaches combined). Left and right turn volumes were assumed to remain at between 10 and 15 % of the through volume of each approach.

The benefits of one scheme over another were found to be very dependent on the volume levels on the major and minor roads. Fig. 3 shows the estimated changes in total delay and fuel costs of priority compared with a one lane roundabout control. Consistent trends in benefits/losses are found as volume levels on the major and minor roads vary and it is possible to draw rough lines of equal benefits/losses. The line of zero loss, representing where the delay and fuel consumption costs of priority and roundabout control are equal, occurs in the top right corner of the figure. That is where volumes on the major and minor roads are relatively high. Comparing priority and roundabout control at this intersection, the roundabout has a nett benefit when total volumes are greater than about 1350 veh/h and the volume on the minor road is greater than 200 veh/h. The benefit of the roundabout increases quite sharply for volumes greater than this. Generally, the benefit of a roundabout increases

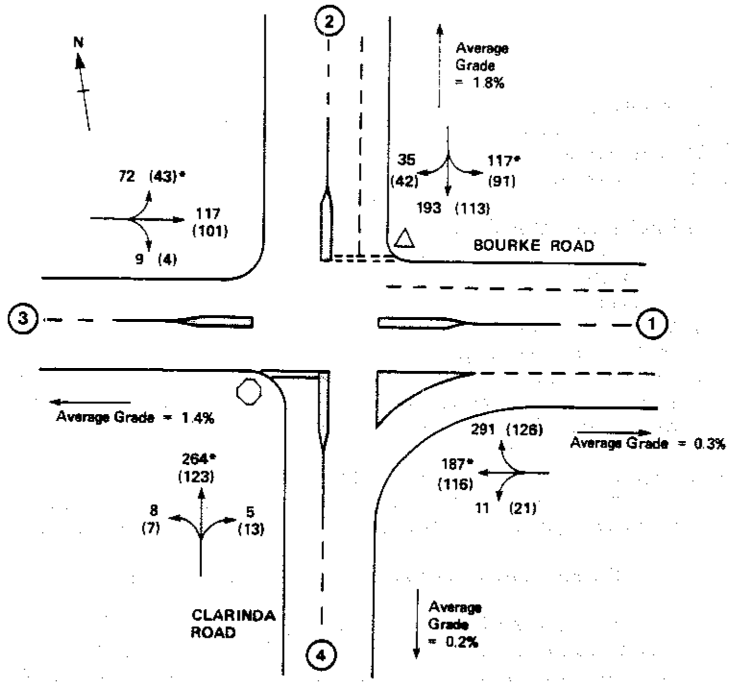

Fig 1. Intersection of Clarinda and Bourke Roads, Clayton South, under priority control.

* Traffic volume (veh/h) in peak period, with off-peak volume in brackets.

as the volumes on the major and minor roads approach each other.

The benefits/losses of priority over VA signal control are shown in Fig. 4. Only for the high volumes tested, total flow over 1400 veh/h, were costs less for signal control. The benefits of priority control for most of the range of volumes tested varied between $5 and $10 per hour.

The benefits/losses of roundabout compared to vehicle actuated (VA) signal control are shown in Fig. 5. The intersection layout for signal control is shown in Fig. 2. For the range of volumes considered, the costs for signal control are only less than those for roundabout control when the volume on the minor road is low, less than about 200 veh/h. This is the cases even for low volumes on the major road. The benefits of signal control over a roundabout are greatest when volumes on the major and minor roads are high and low, respectively.

At a congested priority controlled intersection, an alternative to replacing priority control could be to modify the intersection layout. This was done at the intersection shown in Fig. 1 and simulations were run with the layout shown in Fig. 2. This resulted in lower costs than roundabout or signal

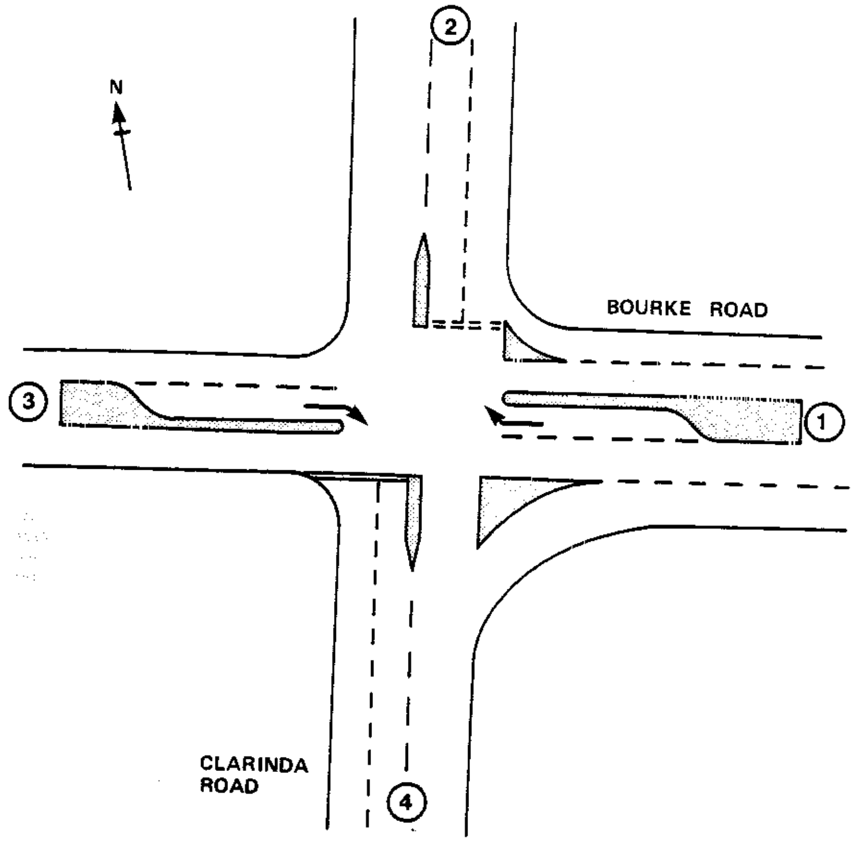

Fig. 2. Layout of the intersection of Clarinda and Bourke Roads, Clayton South, under an alternative design for priority control and under signal control.

control for all of the test volumes (see Figs 6 and 7). Even at the highest test volume (980 and 560 veh/h on the major and minor roads, respectively) the alternative priority had lower costs than the roundabout. Only for the observed peak volumes, which had almost equal major and minor road flows and a large percentage of right turning vehicles, was the roundabout as good. However, in the off-peak conditions, the alternative priority scheme was significantly better than the roundabout (costs $3.58 less per hour). These results suggest that a well designed priority controlled intersection will have lower delay and fuel costs than a roundabout for intersections with flows less than 1600 veh/h. For volumes marginally greater than that, a roundabout will lower costs when flows are similar on each approach and/or when there are significant right turn flows. This value of 1600 veh/h is marginally higher than the value of 1400 veh/h found under the original priority control layout.

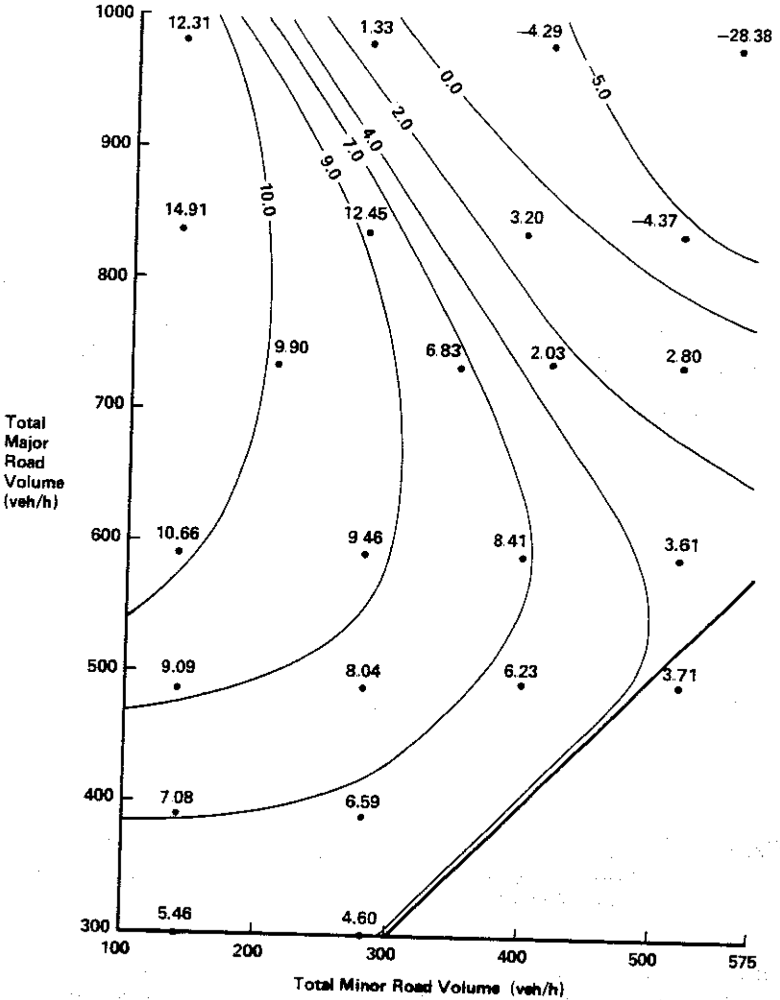

Fig 3. Estimated losses ($/h) resulting from a change from priority to roundabout control at the intersection of Clarinda and Bourke Roads.

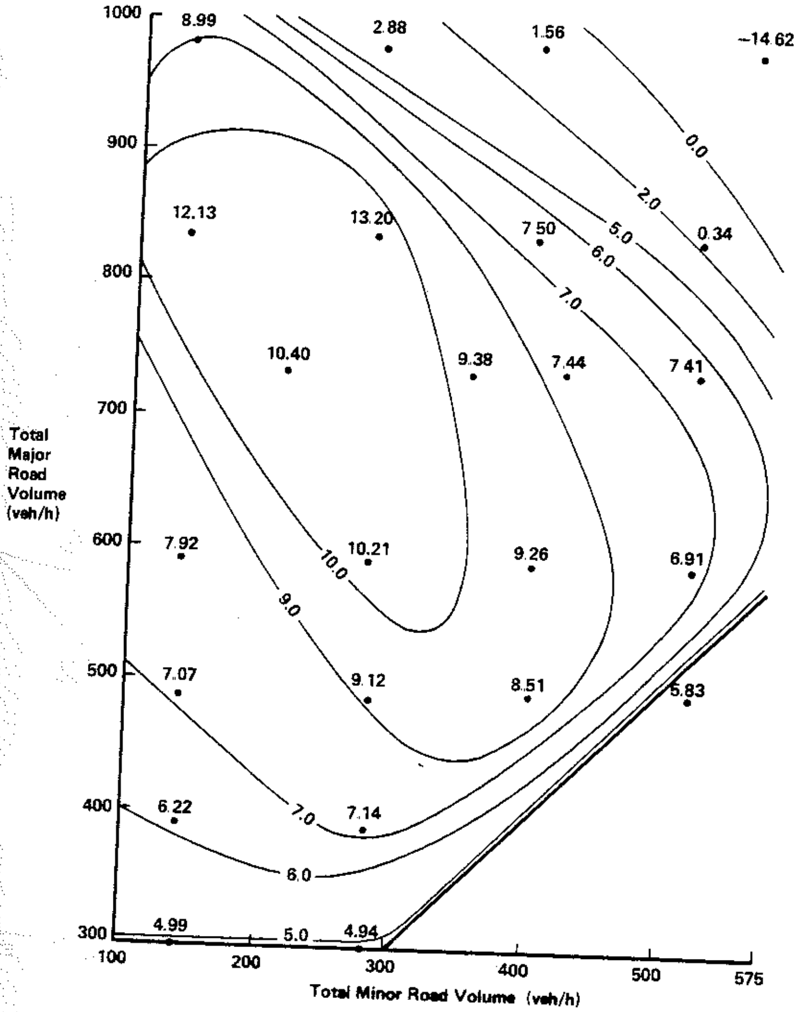

Fig. 4. Estiamted losses ($/h) resulting from a change from roundabout to VA signal control at the intersection of Clarinda and Bourke Roads.

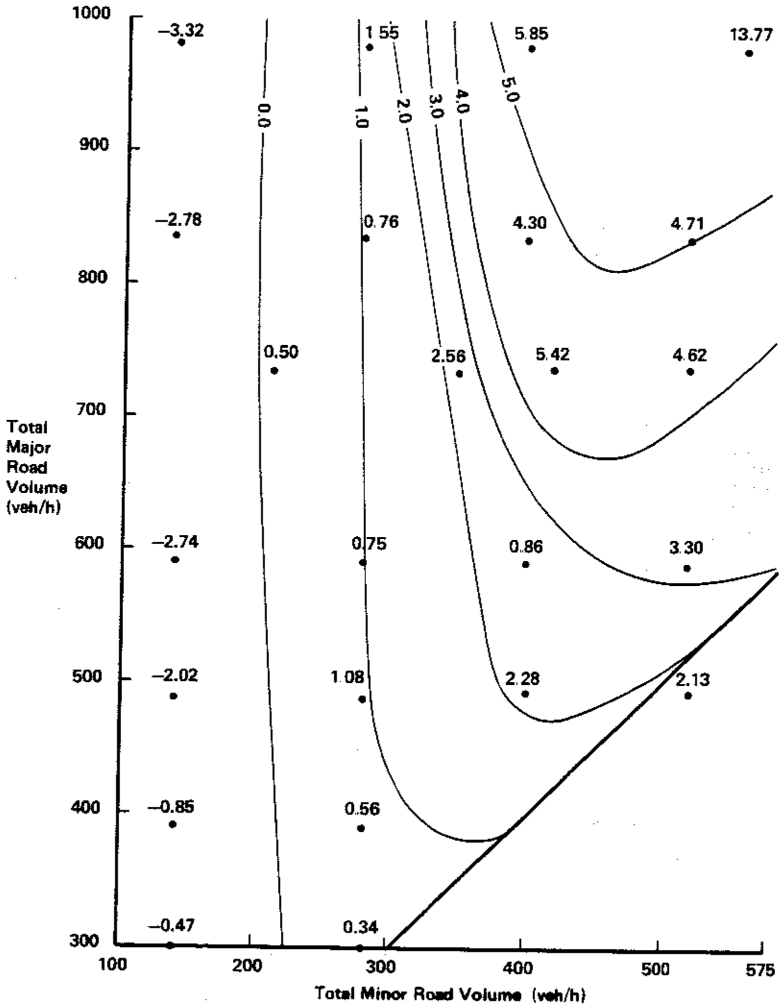

Fig. 5. Estimated losses ($/h) resulting from a change from roundabout to VA signal control at the intersection of Clarinda and Bourke Roads.

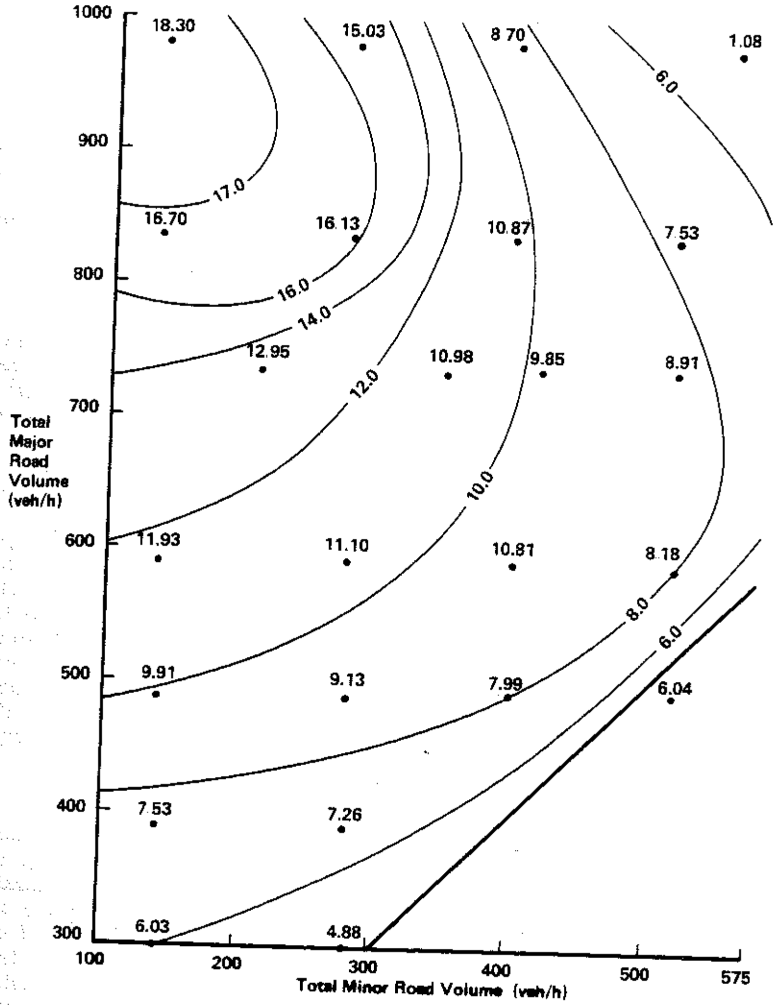

Fig. 6. Estimated losses ($/h) resulting from a change from priority control under the alternative layout to roundabout control at the intersection of Clarinda and Bourke Roads.

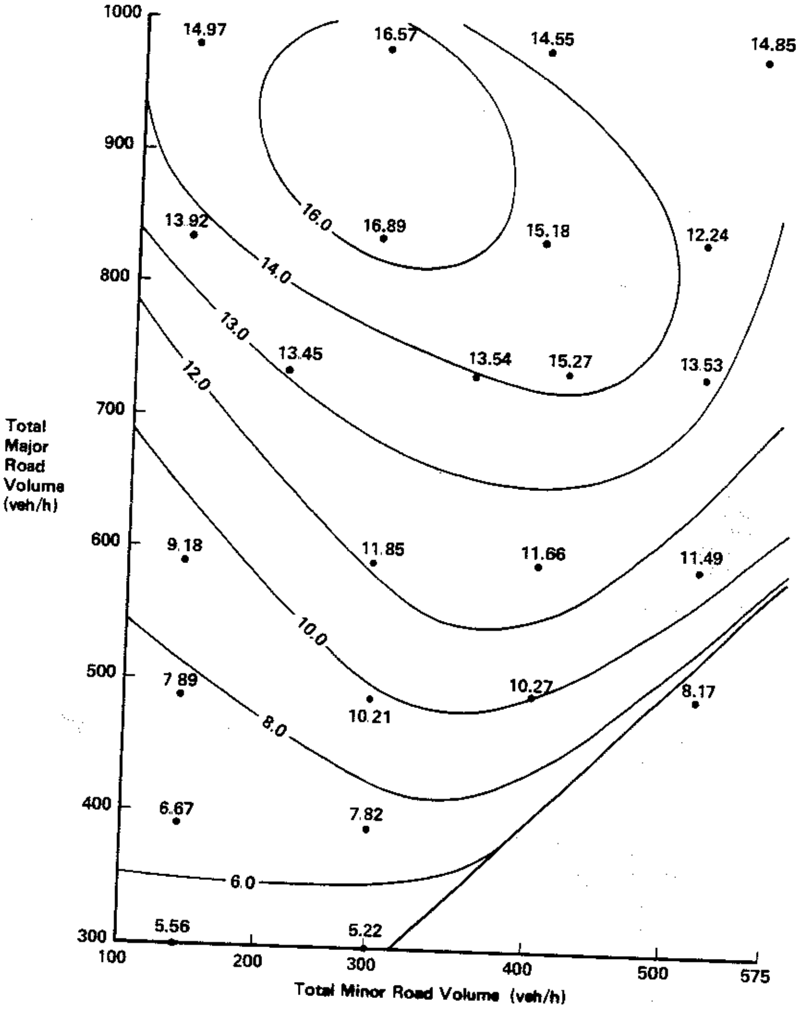

Fig. 7. Estimated losses ($/h) resulting from a change from priority control under the alternative layout to VA signal control at the intersection of Clarinda and Bourke Roads.

The effect of platooning of traffic was tested by assuming that 80 % of the vehicles on one approach of the major road (approach 1 in Fig. 1) came from an upstream intersection during the green phase and the remaining 20 % came during the red phase. The observed peak and off-peak period volumes were used. With peak period volumes, platooning of vehicles on the main approach significantly reduced the costs of priority control, especially with the original priority control. By contrast, costs under roundabout control were marginally greater and under signal control costs were similar. The benefit of roundabout over priority control was reduced from $27.75 to $15.27 per hour for the original priority control and from $0.26 to a loss of $5.01 per hour for the alternative priority control. The platooning had almost no effect with off-peak volumes.

Intersection of Residential Feeder Road with Primary Arterial Road

The intersection of a primary arterial road with a road which services several residential estates is shown in Fig. 8. The heaviest traffic flows, along approach 1, are well platooned by upstream signals. The intersection until recently had priority control but due to the long delays to the minor road traffic and the accident history, signals have been installed. Delay and fuel consumption costs under priority and signal control, including various forms of signal control, are discussed in Bowyer and Biggs (1986). Several of the most interesting results will be discussed in detail here. The total delay and fuel costs, in monetary terms, for the cases considered are given in the Appendix.

The costs under priority and linked signal control during the peak period are very similar. The average delay to vehicles on the minor road is significantly less under linked signal control but is much greater than under VA signal control (see Appendix). However, VA control inflicts a great cost on vehicles on the major road, over $80 per hour. The benefit of linked signal control compared to VA signal control is estimated to be $59 per hour during the peak period. With off-peak volumes, costs under priority control are significantly less than under VA and linked signals ($30 and $22 per hour, respectively).

Complaints from drivers on the minor road of excessively long delay times after the signals were converted from VA to linked control, led to the double cycling of the signals. That is, two cycles were run for every cycle of the upstream intersection. This had the desired effect of reducing delays to vehicles on the minor road, but at the expense vehicles on the major road. Double cycling the linked signals increased total costs by $37 per hour during the peak period. Since no difference in safety would be expected, this would also reflect the nett loss of the change. In this situation drivers on the minor road should be educated to tolerate longer delays so that total intersection efficiency will be increased. Once they enter the main road they will benefit at other intersections provided the maximising of intersection efficiency is carried out consistently

Double cycling was found to work well during the off-peak period when volumes were low, despite the shorter cycle time (108 s compared to 130 s during the peak). With careful adjustment of the flexitime settings, costs could be reduced by $3 per hour by double cycling during this period.

Another method of reducing delays to vehicles on the minor road is to adjust the signal settings. Adjustments to the flexilink settings for the peak

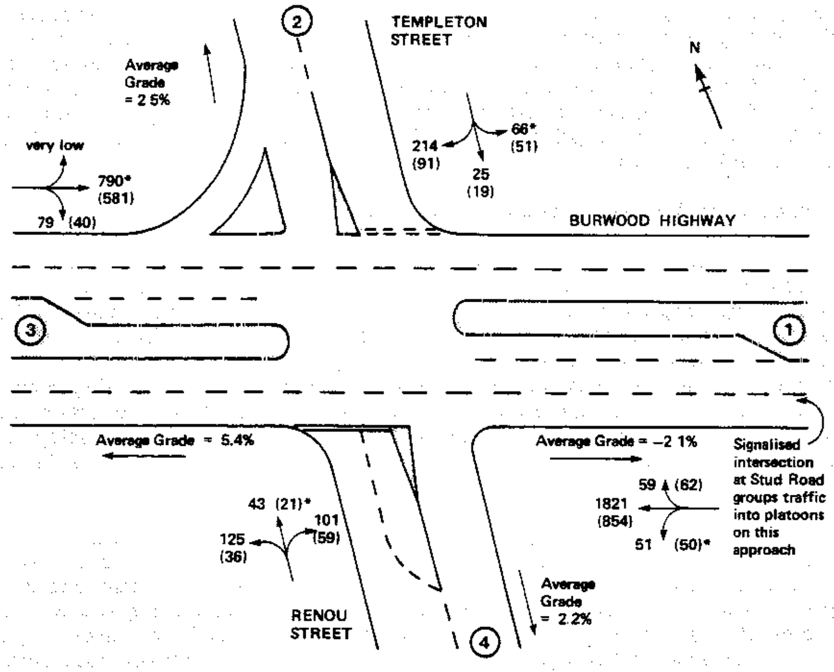

Fig. 8. Intersection of Burwood Highway with Templeton and Renou Streets, Wantirna under priority control

* Traffic volume (veh/h) in peak period, with off-peak volume in brackets

period resulted in an average reduction of 4.5 s in the delay to vehicles on the minor road with almost no change to vehicles on the major road Total costs were almost the same.

An aspect of driver behaviour which can have a significant effect on costs at some intersections is lane discipline while turning. At the intersection shown in Fig. 8 right turning vehicles from the minor road turn into the kerb side lane thus conflicting with the opposing left turning vehicles. The left turning vehicles must therefore wait until all the right turning vehicles have completed their turn before proceeding. Both the cases where left and right turning vehicles did and did not conflict were tested using INSECT. During the peak period the conflict between the turning vehicles caused the delay time of left turning vehicles to increase to a small extent, but its major effect is on the green and red times of the signals. In VA mode the increase in the green time for the minor road caused the delay time of vehicles on the major road to increase. This resulted in an increase in costs of $19 per hour. In flexilink mode the signal settings ensure that the main platoon of vehicles on the major road are undelayed by the signals so the effect on the major road is less. On the minor road the increased green time out-weighs the effect of the shorter delays to left turning vehicles and costs on the minor road are less when the turning vehicles conflict. This would not be the cases in fixed time linked mode or if vehicles on the minor road had a longer minimum green time. The total effect of the lack of lane discipline for flexilink mode in the peak period was found to be $6 per hour. For the low conflict volumes no effect was found.

A common practice for increasing the efficiency of signalised intersections has been to include slip lanes for left turning vehicles. The effect of including slip lanes on the minor roads of the intersection shown in Fig. 8 was investigated using INSECT. As expected, costs decreased for vehicles on the minor road. However, the greatest effect of the slip lanes was to increase the proportion of green time on the major road. This reduced delay time and number of stops for vehicles on the major road which resulted in large cost savings. The total benefit of the slip lanes during the peak period were estimated to be $39/h for VA control and $21/h for flexilink control. The benefit of slip lanes with flexilink control is very sensitive to the degree of platooning on the major road. With the percentage of platooned vehicles decreasing from 92 to 70%, the benefit of slip lanes rose from $21 to $41 per hour. The benefit with VA control remained fairly stable over the different proportions of platooned vehicles. Thus slip lanes provide the greatest benefit when left turn volumes using the lanes are high and, where the signals are operating in VA mode or where they are in linked mode and a high proportion of vehicles are not platooned.

The above finding for slip lanes provides some insight into the potential benefits of allowing vehicles to turn left on a red signal. A small reduction in delay and fuel consumption would occur for those vehicles able to turn left early. However, if left turning vehicles do not have an exclusive lane, many may be blocked by through vehicles and left turning vehicles would the trigger vehicle detector and therefore affect the change of signals. The later effect would negate the large benefit of increased green time on the major road.

CONCLUSIONS

Substantial reductions in travel costs for users of the road system are possible through the choice of the appropriate forms of intersection traffic control. Traffic engineers should endeavour to maximise intersection efficiency. A cost-benefit analysis, taking into account all user costs and the costs of implementing and maintaining the scheme, should be used when making the final decision.

The three major travel costs to be considered when comparing control schemes are travel or delay time, fuel consumption and accident risk. By considering the cruise speed at which people travel, the value of savings in travel time was found to be between $5 and $8 per hour, depending on vehicle and speed. This is greater than the commonly used value of one third of average weekly earning and suggests that the value of small time savings is at least as great as the value of large time savings (per unit time).

Two of the major user costs, delay time and fuel consumption, can be estimated using the traffic simulation model, INSECT. It can model stop, give-way, roundabout and signal control and has been found to provide reasonable estimates of the savings/losses from a change in traffic control or intersection layout. The estimates are therefore suitable for use in a cost-benefit analysis. The prediction of accident risk for an intersection under given forms of control and volume levels is an area for future research.

Several cases are given demonstrating the usefulness of INSECT. At the intersection of a local collector road and a limited arterial road, priority, roundabout and signal control were compared for a range of traffic volumes. User costs were found to be very dependent on the volume levels. Contour type maps of the benefits of one scheme over another for given major and minor road volumes were developed. These showed the trends in benefits and operating conditions under which one scheme was better than another. The results indicate that for total intersection volumes of less than 1300 veh/h delay and fuel costs under priority control are similar to, or less than, under roundabout control. For the intersection volumes tested, all less than 1600 veh/h, roundabout control has lower costs than VA signal control provided volumes on the minor road are greater than about 200 veh/h. However, costs are dependent on the exact layout of the intersection, lane usage, turning volumes, degree of platooning, etc., and each intersection should be modelled to determine the most appropriate form of control. The example given shows the variation in user costs for specific control and layout changes and helps to give the traffic manager a feel for the costs of various schemes.

The second case considered was that of the intersection of a residential feeder road with a primary arterial road. INSECT was found to be suitable for testing a number of control and layout options. Substantial benefits were found for linked over VA signal control during the peak period, but costs were far less for priority control during the off-peak. Linked control resulted in quite long delays on the minor road and the effect of double cycling the linked signals to reduce their delay was tested. Costs increased significantly during the peak, but decreased during the off-peak. The effect of including left turn slip lanes on the minor road was also investigated. The main effect of the slip lanes was found to be the decreased cycle time and increased proportion of green time for vehicles on the major road. Substantial savings in delay and fuel were found for peak period volumes, especially for VA control. At this intersection the lane discipline of left and right turning vehicles was poor and using INSECT this was found to have a significantly effect the delay and fuel costs during the peak period.

ACKNOWLEDGEMENTS

The authors thank the Executive Director of ARRB, Dr. M. G. Lay, for permission to publish this paper. The work reported in this paper was undertaken through a project supported by the National Energy Research, Development and Demonstration Council (NERDDC) of Australia. The views expressed in the paper are those of the authors, and not necessarily those of ARRB or NERDDC.

REFERENCES

AKCELIK, R. (1986). SIDRA version 2.2 input and output. Australian Road Research Board. Technical Manual, ATM No. 19. BIGGS, D.C. and MURPHY, G.J. (1986). Collection of fuel consumption data at isolated intersections. Australian Road Research Board. Internal Report AIR 428-1.

BIGGS, D.C. (1986). Analysis of fuel consumption data collected at isolated intersections. Australian Road Research Board. Internal Report AIR 428-2.

BIGGS, D.C. and AKCELIK, R. (1984). The effects of driver behaviour and vehicle characteristics on fuel consumption: an application of the power model. Australian Road Research Board. Internal Report AIR 390-7

BIGGS, D.C. and BOWYER, D.P. (1986). Simulation of traffic performance at three intersections using INSECT. Australian Road Research Board. Internal Report, AIR 428-3.

BOWYER, D.P., AKCELIK, R. and BIGGS, D.C. (1985). Guide to fuel consumption analyses for urban traffic management. Australian Road Research Board. Special Report, SR No. 32.

BOWYER, D.P. and BIGGS D.C. (1987). Towards more fuel efficient control practices at isolated urban intersections. Australian Road Research Board. Research Report, ARR 147.

DALEY, K. (1984). Traffic Control Systems. In K.W. Ogden and D.W. Bennett (eds): Traffic Engineering Practice', 3rd edition, Department Civil Engineering, Monash University.

LAY, M.G. (1986). Source book for Australian Roads. Third edition. Australian Road Research Board.

NAIRN, R.J. and PARTNERS (1986). Intersection simulation model (INSECT). User Manual. Report to the National Energy Research, Development and Demonstration Council, Dept. Resources and Energy, Australian Government.

STANDARDS ASSOCIATION OF AUSTRALIA (1986). Australian standard manual of uniform traffic control devices. Australian Standard, AS 1742; Part 2, Section 2.

ROYALAUTO (various issues in 1985 and 1986). Royal Automobile Club of Victoria (RACV), Melbourne.

APPENDIX

Results for Intersection of Residential Feeder Road (Templeton Street) and Primary Arterial Road (Burwood Highway)

(a) Peak Period

Control & Volume	User Cost	Major Road	Minor Road	Total
Volume (veh/h)		2798	562	3360
Priority	Fuel	57 mL/veh	109 mL/veh	219.5 L
	Delay	6.0 s/veh	81.6 s/veh	17.4 veh-h
	Cost	$116	$99	$215
VA	Fuel	82 mL/veh	84 mL/veh	276.4 L
	Delay	22.6 s/veh	29.4 s/veh	22.2 veh-h
	Cost	$221	$50	$271
Linked	Fuel	62 mL/veh	96 mL/veh	226.0 L
	Delay	10.0 s/veh	53.1 s/veh	16.1 veh-h
	Cost	$139	$73	$212
Linked, Double-cycle	Fuel	76 mL/veh	88 mL/veh	261.9 L
	Delay	18.0 s/veh	34.3 s/veh	19.3 veh-h
	Cost	$193	$56	$249
Linked, Adjusted	Fuel	62 mL/veh	93 mL/veh	225.7 L
	Delay	10.6 s/veh	48.6 s/veh	15.9 veh-h
	Cost	$142	$68	$210
VA with Slip Lane	Fuel	77 mL/veh	80 mL/veh	261.5 L
	Delay	16.5 s/veh	21.2 s/veh	16.1 veh-h
	Cost	$189	$43	$232
Linked with Slip Lane	Fuel	59 mL/veh	90 mL/veh	216.6 L
	Delay	7.9 s/veh	44.7 s/veh	13.1 veh-h
	Cost	$127	$64	$191
VA with no Conflict on Minor Road	Fuel	79 mL/veh	84 mL/veh	268.6 L
	Delay	19.0 s/veh	28.4 s/veh	19.2 veh-h
	Cost	$202	$50	$252
Linked with no Conflict on Minor Rd.	Fuel	60 mL/veh	97 mL/veh	221.7 L
	Delay	8.5 s/veh	56.0 s/veh	15.4 veh-h
	Cost	$131	$75	$206

(b) Off-peak Period

Control & Volume	User Cost	Major Road	Minor Road	Total
Volume (veh/h)		1572	274	1846
Priority	Fuel	52 mL/veh	82 mL/veh	103.7 L
	Delay	5.0 s/veh	25.6 s/veh	4.1 veh-h
	Cost	$58	$23	$81
VA	Fuel	69 mL/veh	77 mL/veh	128.9 L
	Delay	12.8 s/veh	21.3 s/veh	7.2 veh-h
	Cost	$91	$20	$111
Linked	Fuel	57 mL/veh	90 mL/veh	113.7 L
	Delay	7.7 s/veh	51.1 s/veh	7.3 veh-h
	Cost	$69	$34	$102
Linked, Double-cycle	Fuel	64 mL/veh	78 mL/veh	121.3 L
	Delay	11.5 s/veh	24.1 s/veh	6.9 veh-h
	Cost	$83	$22	$105
Linked, Double-cycle Adjusted grn	Fuel	61 mL/veh	80 mL/veh	118.2 L
	Delay	9.7 s/veh	27.6 s/veh	6.3 veh-h
	Cost	$77	$23	$100
VA with Slip Lane	Fuel	67 mL/veh	73 mL/veh	124.8 L
	Delay	11.6 s/veh	14.1 s/veh	6.1 veh-h
	Cost	$86	$17	$103
Linked with Slip Lane	Fuel	55 mL/veh	84 mL/veh	109.7 L
	Delay	6.6 s/veh	38.3 s/veh	5.8 veh-h
	Cost	$65	$28	$93
VA with no Conflict on Minor Road	Fuel	56 mL/veh	90 mL/veh	113.3 L
	Delay	7.5 s/veh	51.0 s/veh	7.2 veh-h
	Cost	$67	$34	$101
Linked with no Conflict on Minor Rd.	Fuel	68 mL/veh	76 mL/veh	128.6 L
	Delay	12.7 s/veh	20.8 s/veh	7.1 veh-h
	Cost	$90	$20	$110