URBAN ROAD TRAFFIC MODELS FOR ECONOMIC APPRAISAL

C. S. FISK and R. C. M. DUNN
Department of Civil Engineering
University of Auckland

Transit New Zealand Research Report No. 8

ISBN 0-478-04143-8
ISSN 1170-9405

PO Box 5084, Lambton Quay, Wellington, New Zealand
Telephone (04) 499-6600; Facsimile (04) 496-6666

Fisk, C.S., Dunn, R. C. M. 1992. Urban road traffic models for economic appraisal. *Transit New Zealand Research Report No. 8.*

Keywords: benefit:cost analysis, capacity analysis, computer packages, delay analysis, economic evaluation, NETSIM, MULATM, project evaluation, traffic modelling, urban networks

DISCLAIMER

CONTENTS

ABSTRACT

Research for the project, "Urban road traffic models for economic appraisal", identified and developed a range of traffic analysis software suitable for New Zealand use to evaluate urban road improvement schemes. Outputs of the models, in the form of traffic performance characteristics, are used to estimate expected economic benefits from alternative options for a road improvement scheme. This is to allow funding agencies and, in particular, Transit New Zealand, to allocate resources rationally to competing projects.

Criteria were defined for evaluating existing traffic analysis software. Overseas and New Zealand software were then appraised, and detailed analysis of the selected software was conducted.

Research results summarise the analysis and evaluation of existing computer-based packages for intersections, arterial networks, motorways, small area networks and city-wide networks. They also summarise the in-depth investigations of existing models such as NETSIM and MULATM. A summary of theoretical work and accompanying references is given, together with an outline of the program MULDEL. This program was developed to estimate delay at a priority intersection based on the user optimal principle for lane choice.

Economic evaluation obtained from traffic models, including intersection, small area network and city-wide network models, as well as directions for future research required for intermeshing economic evaluation and traffic models are summarised.

1. INTRODUCTION

This section reviews the goals and objectives of project AD/50, "Urban road traffic models for economic appraisal" (Fisk and Dunn 1986, 1987, Fisk 1988a), describes the research approaches adopted, and outlines the report contents.

1.1 Objectives and Goals

The objectives of project AD/50 have been to identify and/or develop a range of traffic analysis software suitable for use in New Zealand for the purposes of evaluating urban road improvement schemes. More specifically the models would produce output in the form of traffic performance characteristics, which could then be used to estimate the expected economic benefits from alternative options for a given project, and subsequently allow a centralised funding agency to allocate resources in a rational manner to competing projects.

The overall goal of this research was to ensure that the economic evaluation analysis of urban road improvement schemes, a prerequisite for obtaining funding from Transit New Zealand, would give consistent and reliable results throughout New Zealand. Initially it was intended that agencies performing such analyses would be required to use software recommended from this research. If this approach is not adopted an additional step would need to be made to ensure that the submodels used in different software packages produce compatible results.

1.2 Research Approach

To achieve the above objectives, the first stage consisted in defining a set of criteria which could be used as the basis for evaluating existing traffic analysis software, as reported in Fisk and Dunn (1986, Stage I). It was also apparent that it would be appropriate to classify software into different categories, according to the degree of network complexity and modelling detail.

The second stage involved appraising software, developed both overseas and in New Zealand, with reference to this set of criteria and classification scheme. This appraisal was based mainly on published information and, to some degree, direct correspondence with the model developers, allowing the researchers to target a subset of packages for a more in-depth study. The results of this appraisal are reported in Fisk and Dunn (1986, Stage II).

In the third stage a more detailed analysis of the selected subset was conducted with the emphasis being on the modelling approaches adopted and, where appropriate, hands-on experience in the use of the software. This led to the recommendation of a set of packages which together address a comprehensive range of traffic problems (Fisk 1988a). It also led to the development of improved modelling approaches, the details of which are contained in a number of reports and papers referenced in Section 2.3.

1.3 Contents of Final Report

Most of the research findings have been published in papers or reports written during the course of this project. The main purpose of this final report is to integrate this work in a single document giving a brief description of the main results without entering into technical details, the latter being available from the aforementioned material.

The results from the research can be divided into two categories: that pertaining directly to the study of different software, and that pertaining to new results vis-à-vis modelling approaches, the latter emerging as an important later focus of the research because of shortcomings revealed in this area. Section 2 covers both aspects, with Section 2.1 reserved for the analysis of the software and Section 2.2 covering developments on modelling issues.

While the project has been orientated towards the study of traffic analysis procedures, it was considered desirable in this final report to integrate this aspect of the planning process with that of economic evaluation to indicate how the output from the traffic models can serve to produce benefit-cost estimates. This question is addressed in Section 3.

Finally the research has served to identify a number of problem areas which would merit from further study, as described in Section 4.

2. SUMMARY OF RESEARCH RESULTS

As indicated above, it is convenient to classify the research into two categories, that dealing with the analysis and evaluation of existing computer-based packages, and that involving model development. These areas are covered separately in Sections 2.1 and 2.2 respectively. To avoid confusion in terminology, a "model" refers to a mathematical model used to represent the behaviour of a system, and "package" or "software" refers to a computer program or set of programs which may include one or more models together with algorithms for obtaining numerical solutions.

2.1 Software Analysis

The first step consisted in specifying a set of criteria which would serve as a basis for comparing different software, with items such as reliability, user interface, and the adaptability of the model components to New Zealand conditions. It was also evident that no single package could cover the entire range of urban network problems and that it would be necessary to categorise packages according to their area(s) of application. The classification used is based on two main features, namely network complexity and modelling detail. The former relates largely to the components of the network being analysed, a convenient category being intersections, arterials, motorways and/or motorway corridors, small area networks, and city networks.

The question of modelling detail arises because generally, as the magnitude of the impacts from an improvement scheme decreases, model accuracy should increase to ensure that the predicted differences between two alternative options are not largely attributed to modelling and/or data errors. The most convenient categorisation in this regard is the distinction between strategic and operations planning models, the former being characterised by a long-term planning horizon and involving major structural changes to the transportation system, and the latter by a shorter planning horizon with minor changes directed at improving the efficiency of the existing system. Operations planning can be further stratified into tactical planning (e.g. 1-5 year planning horizon) and operational planning (which affects the day-to-day operation of the system).

Modelling detail is reflected first by whether averages or individual vehicle characteristics are modelled. In the former the problem is usually analytical in nature while the latter uses a microscopic simulation approach in which individual vehicles are displaced on the network in small time increments, their movements being determined from a set of submodels which represent individual vehicle (driver) behaviour.

Analytical models can be further stratified depending on the level of aggregation of the network representation. Generally small area network problems require a detailed network representation, with intersection delay being modelled explicitly for each turning movement, taking into account conflicting turning movement flows. City-wide network models usually contain a lower level of detail with link and intersection delay obtained from empirically based relationships representing flow information in a more aggregate form. However the current trend in this range of software is to develop a more detailed intersection modelling capability.

As a rough guide, operational planning can be most appropriately modelled using dynamic microscopic simulation, tactical planning using analytical models with a high level of detail, and strategic planning using analytical models with a relatively lower lever of detail. This correspondence is further reinforced by the fact that the input data for the planning horizon decreases in accuracy as the planning horizon increases.

With regard to the software analysed, it is appropriate to mention at this point that in some cases a complete evaluation could not be carried out because software developers did not always respond to requests for information. It must also be recognised that most existing software is being continually updated and enhanced and that new software is being developed periodically. This research project AD/50 largely focused on the status of existing software in the period 1986-1989.

2.1.1 Intersection Software

Software in this category predicts traffic performance characteristics at an isolated intersection and can be conveniently grouped according to whether the intersection is signalised or non-signalised, although some packages address both categories. For signalised intersections, timings may be obtained based on delay minimisation or other criteria.

For a detailed simulation analysis, NETSIM (FHWA 1989) was recommended (Fisk 1988a, Stage III, Volume 1), mainly because of the modelling approaches adopted but also because it appeared to be the best developed analysis tool for small networks. More information is provided in Section 2.2. The remaining discussion in Section 2.1 is restricted to analytical (macroscopic) intersection models.

2.1.1.1 Priority Intersection Software This study of existing priority intersection software investigated modelling approaches, most of which were based on the steady state assumption, a condition not likely to be realised in practice, particularly during peak periods when input flow rates vary considerably. The outcome of this approximation is that delay and other performance measures may be significantly higher than actual values with this tendency increasing as traffic flow approaches saturation.

The software, ARCADY and PICADY for roundabouts and priority intersections respectively, developed at the Transport and Road Research Laboratory (TRRL) in the UK, overcame this by representing the queueing problem in an approximate manner as a dynamic M/M/1 queue (Kimber and Hollis 1979). The average service time is taken to be the inverse of capacity; this tends to slightly over-estimate average service time in low priority flow ranges because of the shorter service time of non-queueing non-priority vehicles. Also for the TRRL method, the dynamic M/M/1 delay curve is approximated using an intuitively based approach known as the co-ordinate transformation technique, an approximation which can be justified *a posteriori* by showing that it closely reproduces the exact dynamic curve.

The TRRL research has led to a major breakthrough in overcoming the problems inherent in steady state models. Their software was not considered appropriate for application in New Zealand mainly because capacity is estimated using a regression model which is approach-based rather than lane-based. Gap-acceptance models for estimating capacity have been successfully used in both New Zealand and Australia, are lane-based, and require less calibration effort than the empirical approach adopted at TRRL.

This investigation led to a number of research papers directed at extending Tanner's (1962) capacity formula to more general situations, extending the dynamic queueing approach developed at TRRL to obtain delay formulae for more general situations, and modelling lane choice when more than one lane services a traffic movement. A validation of the resulting models shows that consistently good results were obtained, with more details given in Sections 2.3.4-2.3.6 and 2.3.9. The results have been incorporated into a practitioner's guide on the performance analysis of priority intersections prepared for Transit New Zealand (Gabites Porter Ltd 1991) and held on file.

2.1.1.2 Signalised Intersection Software Models in this category of intersection software are designed to predict traffic performance characteristics at a signalised intersection and, in most cases, determine timings based on delay minimisation or other criteria. The research finally focuses on SIDRA (Akcelik 1981) for which two desirable characteristics are that the analysis is lane-based and the approach used for delay estimation is compatible with the dynamic approach recommended for priority intersections.

Two qualifications are made in recommending SIDRA. First, it is not as user friendly as one would hope, although the recently released interactive version is a significant improvement over previous versions. Second, a detailed analysis of the modelling procedures was hampered by the difficulty of obtaining a precise understanding of the model theory from the documentation available.

2.1.2 Arterial Network Software

Software in this category is primarily designed to provide signal timings for progressive signal systems and/or give measures of performance on an arterial network. At the microscopic level, NETSIM was recommended as it can analyse fixed-time or traffic-actuated controllers but not a SCATS-operated system (Sydney Co-ordinated Adaptive Traffic System). For example, the program SCATES (Sims 1989) has been developed for such a purpose but, because it has been only recently released with limited documentation on modelling aspects, it was not investigated.

MAXBAND (Little *et al.* 1981) was recommended for producing offsets, cycle lengths and phase sequences, to give a good traffic progression on an arterial or small arterial network, the modelling approach being based on optimisation of the band width.

2.1.3 Motorway and/or Motorway Corridor Software

It was recommended (Fisk and Dunn 1986) that the program FRESIM be procured from McTrans (University of Florida, USA) as soon as the significantly modified new version becomes available. FRESIM adopts a microscopic simulation approach with driver behaviour submodels that are compatible with those in NETSIM, to give traffic performance results for a motorway segment. As noted later in 2.2.1, the FHWA are planning to release, late in 1992, enhanced versions of the simulation programs CORFLO (corridor simulation) and FREEFLO (freeway simulation).

A number of programs based on macroscopic modelling approaches were studied but reservations were expressed about the validity of the modelling approaches (Fisk and Dunn 1986).

2.1.4 Small Area Network Software

At the microscopic levels, NETSIM was recommended for prediction traffic performance characteristics on small area networks. Of all the microscopic simulation programs available this has been the most widely validated and is used extensively in North America by both practitioners and researchers. NETSIM has no travel-demand component, the flows being generated stochastically from user-supplied information.

Macroscopic small area models are usually able to determine route choice, given an origin-destination (o-d) trip matrix, and produce the resulting traffic performance characteristics as output. Of the models supplied, MULATM (Taylor 1989) was recommended although further developments and testing would be necessary (see Sections 2.2.2 and 4.1).

2.1.5 City-wide Network Software

The software in this category is primarily targeted for strategic planning analysis. Of the packages available, EMME/2 (INRO 1986) was strongly recommended, its main features being an innovative design based on a databank concept, extensive graphics capabilities, user flexibility in model specification, and the incorporation of state-of-the-art research with regard to mode choice and assignment (Dunn 1989). While other packages did not appear to have the same level of sophistication in this regard, it is noted that they are being enhanced on a regular basis.

2.2 In-depth Investigation of NETSIM and MULATM

Of all the software investigated during the course of the project, NETSIM and MULATM were subject to the most detailed analysis. The research focused on modelling approaches, calibration requirements, and testing. The main findings from these analyses are summarised below.

2.2.1 NETSIM

The results of an initial study of the submodels and calibration requirements of NETSIM are summarised in Fisk (1987). Further work was undertaken as part of a Masters programme by H.H. Tan, project TM/21, supported by the Traffic Committee, Transit New Zealand. The main objectives of TM/21 were to assess the calibration and validation effort required to implement NETSIM and to carry out this task for selected submodels. The results of this investigation are summarised in Dunn and Tan (1989, 1992) and in more detail in Tan (1989).

The main conclusion drawn as a consequence of these studies is that NETSIM should prove to be a valuable traffic analysis tool, both in research and practice. Most of the submodels investigated were found to be compatible with New Zealand driver behaviour and some of the submodels have been calibrated for New Zealand conditions. Before the program is used in practice, additional work is required in the following areas.

First the fuel data embedded in NETSIM must be replaced with values corresponding to New Zealand vehicle characteristics. These values can be obtained from a fuel model calibrated for New Zealand conditions, such as the Australian Road Research Board (ARRB) instantaneous model shown in Stage III, Report No. 3, Section 2.5 (Fisk 1988a).

Second, some submodels require validation and/or calibration. More details are given in Dunn and Tan (1989, 1992).

Most of the research on NETSIM was conducted using an incomplete version of TRAF-NETSIM (FHWA 1989). TRAF-NETSIM is a significant enhancement of the original NETSIM model and is designed to be used as a stand-alone model or as part of the TRAF suite of programs. An enhanced TRAF-NETSIM version became available towards the end of the research (Tan 1989), a package which included graphics and interactive data input modules. As noted in Dunn and Tan (1992), more recent versions have further enhancements and a new version TRAF-NETSIM is planned for release by FHWA later in 1992. This version will include the possibility of using NETSIM with other simulation programs, namely CORFLO (corridor simulation) and FREFLO (freeway simulation).

2.2.2 MULATM

An in-depth analysis of the submodels in MULATM used published information together with source code listings of the modules. Results are in Stage III, Report No. 3 (Fisk 1988a) and in Fisk and Tan (1988, 1989). The main objective of this analysis was to identify modelling areas for possible enhancement, and many of the suggestions were incorporated in MULATM version 3. This program also had input from other New Zealand users as has version 4, now renamed TrafikPlan.

The analysis and partial programming of two modelling improvements have been carried out as part of Project AD/50, namely delay analysis at priority intersections (Fisk and Tan 1989), and a lane-choice model which will allocate flow to competing lanes at intersections to equalise delay on the lanes used for a given turn. Lanes which are not used will have a longer delay. The lane-choice algorithm has been tested by embedding it in a program, MULDEL (held at Transit New Zealand) which estimates delay at priority intersections (Section 2.4.1), and this program was used as the basis for including a similar but generalised analysis in the New Zealand version of MULATM 3 (MULATM-NZ). During 1990, further tests with MULATM were undertaken by Transit New Zealand.

2.3 Summary of Theoretical Work

A number of modelling issues were addressed during the course of Project AD/50, aimed to improve existing modelling methodology. The results have been recorded in a set of papers submitted for publication in leading international journals, or in some cases in short reports. The decision to submit the papers for publication was made in part so that they would be refereed by leading researchers overseas, thus serving to validate the results and in part so that they would have wider circulation of the ideas and hence have the widest possible impact on developers of traffic analysis software.

The main results from this work are summarised in Sections 2.3.1-11, the headings corresponding to the titles of the relevant papers or reports. Papers submitted for publication in journals are listed in Section 5, References.

2.3.1 On Combining Maximum Entropy Trip Matrix Estimation with User Optimal Assignment

This paper (Fisk 1988b) reports the results of an investigation into the procedure by which the traffic assignment program SATURN (Van Vliet 1982) is combined with the trip matrix estimation program ME2 (Van Zuylen and Willumsen 1980) to produce an estimate of a trip matrix, given link-traffic count data. ME2 was designed to handle a network with flow-independent travel time functions and requires information on the proportion of o-d flow to be assigned to each route between a given o-d pair. With constant link travel times, this proportion can be determined for a given route-choice assumption. For example an all-or-nothing assignment will put all flow onto the shortest path.

In combining ME2 with SATURN, initial proportions are obtained assuming an all-or-nothing assignment with travel times, given by the free flow values. A trip matrix is then estimated and this is reassigned using SATURN with the embedded flow-dependent travel time functions. Based on this equilibrium assignment, new proportions are obtained and the matrix is re-estimated. This procedure is repeated until a satisfactory level of convergence is achieved.

The contribution of this paper (Fisk 1988b) showed that the above procedure does not in fact solve the problem and, although it may converge to a result, it is the solution to a different problem. This was demonstrated by formulating a single mathematical problem for the congested trip matrix estimation problem based on maximising the entropy. The results were sent to the developers of ME2 and have led to the investigation of appropriate solution algorithms by researchers at the Transport Group, University of London.

2.3.2 A Note on the ARRB Model of Fuel Consumption

This note (Fisk 1989c) was written following a study of the ARRB suite of fuel consumption models (Biggs and Akcelik 1986) to clarify the interpretation of the parameters associated with the drag component of the model. The point was a minor one but generated considerable debate with the ARRB researchers and a rejoinder was written which appeared in the same issue of Transportation Research. At this point the two camps have agreed to disagree.

2.3.3 Trip Matrix Estimation from Link Traffic Counts - the Congested Network Case

This research (Fisk 1988b, 1989b, Fisk and Boyce 1983) followed that reported in Section 2.3.1 to try to identify the most suitable approach for estimating a trip matrix from link traffic count data. The best known three formulations of the problem were studied to determine the differences to be expected in the results. Although the different formulations used the link count data in different ways, it was shown that, provided the model assumptions were satisfied, the same trip matrix solution would be obtained for each approach.

This is a surprising but important result because only one of the approaches can be readily solved for large networks. This will be studied further, beyond Project AD/50, using submodels available in EMME/2.

2.3.4 Priority Intersection Capacity - a Generalisation of Tanner's Formula

In this paper (Fisk 1989a), Tanner's (1962) capacity formula is extended to encompass any number of lanes of priority traffic with the possibility of a different gap acceptance parameter for each lane. This problem was investigated as part of a study into delay functions for priority intersections. The capacity result is required in the delay model, its role being to approximate the service rate of non-priority vehicles.

2.3.5 Delay Analysis for Priority Intersections

This research (Fisk 1989d, Fisk and Tan 1988, 1989) began because an analysis of existing delay models at priority intersections showed that all approaches currently being used had some shortcomings. Delay models were developed using the M/M/1 queueing model approximation together with the co-ordinate transformation technique (Section 2.1.1.1) to give analytical delay models for non-priority traffic. The approach differs from that taken at TRRL in that capacity is estimated using Tanner's extended formula (Section 2.3.4), and that the analysis is done on a lane-by-lane basis. Also the co-ordinate transformation technique is extended so that it can represent the case where two different non-priority turning movements share a lane.

Comparisons of predictions with those from other models showed that consistently reliable results were obtained as well as good agreement with data collected in New Zealand at two different sites (Rosser and Milne 1981).

As noted in Section 2.1.1.1, it was envisaged that these models would provide the theoretical basis for software to analyse priority intersections. The generalised results have been incorporated into MULATM (now TrafikPlan).

2.3.6 Lane Choice Analysis for Traffic Assignment

In intersection delay analysis, when one turning movement can use more than one lane, the amount of flow appearing on each competing lane must be known. A model was developed which based the allocation on the user optimal principle or, in other words for a given turning movement, delays on lanes which are used are equal and delays on lanes which are not used are at least as long (Fisk 1990a).

This theory was incorporated in MULATM-NZ. As noted in Section 2.3.5, it was envisaged to develop the results into software.

2.3.7 Link Travel Time Analysis for Traffic Assignment

This research (Fisk 1991b) was undertaken to simplify the task of providing link-travel functions for traffic assignment. Usually functions are obtained by calibrating empirical speed or travel time/flow functions with observed data. This is a costly exercise and, because only a few points can be obtained, the accuracy of the results over the entire flow range is somewhat uncertain.

The approach taken was to adopt a travel time model developed by Cowan (1980) and develop it to a form which would be suitable for inclusion in traffic assignment. The model is based on the assumption that passing cannot occur, and would thus only be realistic on a link with one lane or in high flow ranges where overtaking would be unlikely. Cowan's results are derived given assumptions on the arrival pattern of traffic entering the link, and the free flow-travel time distribution. The resulting expression for the mean travel time is retained in integral form.

Research on this model showed that the results were relatively insensitive to different arrival distributions, and in fact a random arrival model gave results close to the more general Borel-Tanner distribution. Adopting this simplifying assumption, a realistic free-flow travel time distribution was found which would lead to a closed form analytical expression for the mean travel time. The model parameters relate to the mean and variance in free-flow travel time, and a lower bound estimate for individual travel time.

2.3.8 Effects of Heavy Traffic on Network Congestion

Analytical models are developed in Fisk (1990b) for obtaining travel times on links, and capacity and delay at priority intersections when traffic consists of a mix of cars and heavy vehicles. Car and heavy vehicle characteristics (e.g. tracking headways, critical gaps, free flow-travel time distributions) are incorporated directly in the models. As well as providing analytical models for each class of traffic, the results serve to highlight some deficiencies of the passenger car unit (pcu) approximation.

2.3.9 Traffic Performance at Roundabouts

Capacity, delay, and queue lengths are derived by Fisk (1991a) for roundabouts based on the theory referred to in Sections 2.3.4, 2.3.6 and 2.3.8. Where vehicles have a choice of approach lanes, they are assigned to equalise delay on the lanes which are used (i.e. the user-optimal principle). The capacity and delay results are obtained by extending the theory developed for priority intersections. As noted in Section 2.1.1.1, it was envisaged that these results would be developed into software.

2.3.10 Comment on the Paper "Gap-Acceptance and Empiricism in Capacity Prediction" by Kimber

Kimber's (1989) paper presents the viewpoint that the empirical approach to estimating capacity at priority intersections and roundabouts is more acceptable than the gap acceptance approach based on Tanner's model. An unpublished response by Fisk indicated some shortcomings of the experimental method used to compare the approaches, and pointed out that Tanner's gap acceptance model could be extended along several lines to better reflect traffic behaviour. Also it was shown that there is good agreement between gap acceptance results and roundabout capacity data collected in New Zealand.

2.3.11 Unpublished Reports and Notes

Several unpublished documents were written during the course of this project, some giving more details on the priority intersection traffic performance models, and others related to modelling issues which arose from to time to time. The principal papers are:

i. **Traffic performance characteristics at priority intersections**
This report (Fisk and Tan 1988) was written to reinforce the findings referred to in Section 2.3.5. It also includes an analysis of the delay model developed by Rosser and Milne (1981) and presents graphical comparisons to illustrate the conclusions drawn regarding different modelling approaches.

ii. **Traffic performance at priority intersections : analysis details**
This report (Fisk 1989d) was written to give more detailed results on priority intersection delay based on the theory referred to in Section 2.3.5. Specifically this theory is applied at intersections having different turning movements and lane-sharing configurations leading to analytical results in each case.

The analysis was subsequently incorporated into a computer program (MULDEL, Section 2.4.2) and, during its development, a more acceptable result was found for major road left turners which under New Zealand rules must cede to opposing right turners.

Other short notes included a discussion on the criteria appropriate for checking convergence of equilibrium assignment, on design queue lengths to complement the delay analysis for priority intersections, and on modelling issues with the focus on the appropriate level of network detail.

2.4 Computer Programs

2.4.1 FORTRAN Programs

FORTRAN programs have been used for producing the numerical results, and subsequently graphs, for the papers described in Sections 2.3.4-2.3.10.

2.4.2 MULDEL

The program MULDEL was also developed which solves the lane-choice problem in conjunction with priority intersection delay analysis. MULDEL incorporates the theory given in Fisk and Tan (1989) and Fisk (1989d) to produce estimates for delay at a priority intersection. It was written to provide the basic analysis required for MULATM to improve the lane choice and priority intersection delay components.

The program requires a description of the intersection similar to that used in MULATM: for each approach lane the turning movement pattern is given as one of the nine possible types described in Report No. 5 (Fisk 1988a) or, given the flow data for each turning movement, flow by lane is estimated together with the corresponding delay.

The program can analyse an intersection with three or four approaches and up to four lanes on each approach. The non-priority approaches may have up to two lanes for a left or right turn movement while the priority approaches may only have one lane for left or right turns.

The first task is to determine, for the turning movement in each lane, the turning movements in other lanes which enter into conflict. The nature of the turning movement together with the conflicting pattern determines the delay type, with 23 different delay types, each of which has a distinct capacity and delay formula. In conjunction with delay estimation, where a choice of lanes is available, an iterative algorithm is used to place turning flows in lanes in a manner so that, at convergence, the delays on lanes used are equal, and the delays on lanes which are not used are higher. The problem is in fact a mini-assignment problem, and can be solved using an algorithm designed to solve the traffic equilibrium assignment problem.

The algorithm currently embedded in MULDEL is based on the nonlinear Jacobi method for solving the assignment problem which has the mathematical form of a variational inequality. In each iteration of this procedure, the delay function for a turn in a given lane is approximated by fixing the flows on other conflicting turning moments at the values obtained in the previous iteration and the assignment problem is then solved for these approximate functions. This sub-problem is also an equilibrium assignment problem but the structure of the approximate delay functions allows it to be solved as an optimisation problem. Currently in MULDEL it is solved using the fixed step length method which is straightforward to implement but very inefficient. The Frank-Wolfe algorithm widely used in equilibrium assignment programs was also considered but it did not appear possible to obtain analytical expressions for the integrals of the delay functions, as required by this algorithm.

As an enhancement, it is recommended that an alternative, more efficient, algorithm be implemented. The most obvious choice is the Newton approach which would consist in approximating the delay functions by their first order Taylor series expansions. The assignment problem with these linear functions has the form of a linear complementarity problem for which standard algorithms are available. Following solution of the linear sub-problem, the linear approximation would be improved by expanding the delay functions about the preceding solution, and the process repeated until satisfactory convergence is obtained.

3. ECONOMIC EVALUATION

Approximately four to six months of project time was allocated to a study for estimating the economic benefits of a road improvement scheme, with TR9 (Bone 1986) forming the starting point. Most of the results are reported in Fisk (1988a). In this final report, it is considered appropriate to indicate how traffic models output could be used to obtain benefit measures, and to identify areas where further work is needed to achieve this.

3.1 Limitations of TR9

A number of extensions to TR9 (Bone 1986) would be required before its methodology can be applied directly to estimate the user benefits of an urban road improvement scheme using traffic performance output data from traffic models. The main limitations of the current approach are as follows:

1. TR9 is basically a manual procedure whereas the complexity of the problem in the urban context requires a computer-based approach, particularly for network problems.

2. Some operating cost submodels in TR9 incorporate a lower level of detail than that required of the more detailed network and intersection traffic models. The operating cost submodels should be tailored to match the same level of detail as the traffic model.

3. The maintenance and repair submodel in TR9 is tailored more for rural than urban roads, with costs taken as a function of road roughness and distance travelled. In the urban context, cornering and stop-start cycles are likely to contribute significantly to wear and tear.

4. Travel demand is not considered explicitly. The role of travel demand models in the estimation of benefits is highlighted below.

From the above, it is clear that some additional effort is required to adapt the TR9 procedure to the problem of estimating economic and user benefits using traffic model output data. This includes issues raised by the above comments as well as by such questions as the valuation of travel time, the estimation of accidents and their associated costs. More fundamentally from a practical point of view, it is necessary to readily interface traffic performance information with programs for estimating the corresponding user cost.

3.2 Traffic Models and Economic Evaluation

Benefits are estimated using actual resource costs of travel, whereas travel-demand estimation is based on user-perceived cost. The latter is likely to be some combination of travel time and operating cost, with the appropriate expression being obtained as part of the calibration exercise. If the user-perceived cost is not accurately represented in the travel-demand model, erroneous demand predictions may be obtained. Further discussion on this issues can be found in Fisk (1988a).

Taking into account the likelihood that resource and perceived costs would be different, the general expression for user benefits, B, is (Fisk 1988a):

$$B = \sum_{ijmr} (T_{ijmr} + T'_{ijmr})(p_{ijmr} - p'_{ijmr})/2 + T_{ijmr}(c_{ijmr} - p_{ijmr}) - T'_{ijmr}(c'_{ijmr} - p'_{ijmr}) \qquad \text{Equation (1)}$$

where T_{ijmr} is the number of trips from zone i to zone j by mode m on route r
p_{ijmr} is the perceived cost from zone i to zone j by mode m on route r
c_{ijmr} is the resource cost of travel from zone i to zone j by mode m on route r

The prime superscript (′) identifies the same entities for the proposed scheme. In the following, this expression is simplified for the different categories of traffic model.

3.2.1 Intersection Models

For analytically based intersection software such as SIDRA and MULDEL, turning movement flow is supplied as input. The allocation of turning movement flow to alternative lanes has the form of a mini-assignment problem as discussed in Section 2.4.2. If flows are allocated to lanes using the user optimal principle, the perceived costs on lanes used for a given turning movement will be equal and it is straightforward to show that the perceived cost terms in equation (1) cancel out. (Note: SIDRA adopts the principle of equal degrees of saturation to obtain lane flows, but results show this is close to the user optimal solution.)

In NETSIM, lane choice could be expected to roughly correspond to user optimal choice (with a tactical lane change being made if the driver has the expectation of reducing travel time, and not being made if a gap is unavailable). In any event NETSIM does not output delay characteristics by lane, so that for economic evaluation it would be necessary and reasonable to perform the analysis at the turning movement level.

Another feature of NETSIM is that turning movement flows are generated stochastically from user supplied proportions and this, together with other stochastic components of the program, implies that different runs produce different answers. To ensure that the difference in estimated benefits between two schemes is not largely related to the stochastic element it would be necessary to perform a number of runs for each scheme and to take averages.

Taking into account the above discussion, the benefit measure, B, reduces to:

$$B = \sum_{k=1}^{K} f_k(c_k - c'_k) \qquad \text{Equation (2)}$$

where K is the total number of turning movements, f_k is the flow for turning movement k, and c_k and c'_k are respectively the unit resource costs associated with turning movement k, for the existing and proposed schemes.

For a good approximation, the components of c_k related to wear and tear and use-related depreciation will be similar for all schemes and hence cancel out. The remaining components arise from travel time, fuel consumption, and accident costs.

The ARRB elemental fuel model (Biggs and Akcelik 1986), which estimates fuel consumed separately for stopped, accelerating, decelerating, and cruise modes, gives the appropriate level of accuracy for the macroscopic analytical models (e.g. it is embedded in SIDRA). NETSIM estimates the fuel consumed for each vehicle each second, using built-in data arrays with speed and acceleration determining the appropriate element in the matrix. These tables would be replaced by values appropriate for the New Zealand vehicle fleet. The values would be most appropriately derived from the instantaneous ARRB fuel consumption model as this would ensure compatibility with the elemental model used at the macroscopic level. A derivation of a fuel consumption model for NETSIM is given in Fisk (1988a) and it essentially consists of integrating the instantaneous model over a one-second time interval.

3.2.2 Small Area Network Models

For NETSIM the demand components will be the same for all alternatives with the qualification that a small difference will be caused by the stochastic generation of flows and driver characteristics. Taking into account the discussion in the preceding section, the perceived cost terms in equation (1) cancel and the resulting benefit measure, B, reduces to:

$$B = \sum_{k=1}^{K} f_k(c_k - c'_k) \qquad \text{Equation (3)}$$

Here f_k is the flow on link k, a link being either the blockface portion of a road or the turning movement at the intersection.

For MULATM and other small area assignment models, provided that route choice is user optimal with respect to perceived costs, the benefit measure reduces to that given in equation (3).

The discussion in Section 3.2.1 with regard to fuel modelling applies to this case. It is planned to incorporate a fuel model in a future release of MULATM and, for both NETSIM and MULATM, submodels for estimating the remaining vehicle operating costs would be required (Section 3.1).

Similar results to those derived above are valid for the recommended arterial and motorway traffic analysis software.

3.2.3 City-wide Models

An application of software in this category would usually include traffic assignment together with one or more travel-demand models. In the most general case, assuming that traffic assignment is based on the user optimal principle (with respect to perceived costs) as is the case for most assignment modules of strategic planning packages, equation (1) reduces to:

$$B = -\sum_{ijm} (T_{ijm} + T'_{ijm})(p_{ijm} - p'_{ijm})/2 + \sum_{ijmr} (T_{ijmr}c_{ijmr} - T'_{ijmr}c'_{ijmr}) \qquad \text{Equation (4)}$$

The second term is the actual benefit from an improvement, giving the first term an interpretation of a form of user's surplus.

If this theory is to be faithfully applied, it implies that a single measure of perceived cost needs to be incorporated in all travel-demand models and, more significantly, that travel demand by mode, destination, and route, needs to be estimated simultaneously from a single travel-demand model. The usual procedure is to perform trip destination, mode choice, and route choice in sequence. However this approach is incompatible with the requirements of economic analysis. Using a single model to estimate all components of travel demand mainly implies that travel choices are made consistently because the user-perceived cost is the same for all trip-making decisions.

The trend in the development of software in this category is to achieve this consistency, notably between the destination or mode choice components and traffic assignment. This is obtained either using an iterative procedure which ensures that, in the final result, travel time used in the demand models is the same as that which would be obtained from the resulting level of network congestion or, in the case of EMME/2, of being able to solve the mode choice and assignment problems simultaneously.

Travel times may not be the only component of user-perceived cost and vehicle operating costs are also likely to be a factor but usually perceived to be below the resource cost.

The above discussion has two major implications for deciding the approaches appropriate for obtaining an estimate of benefits for a proposed road improvement scheme. First it is clearly necessary to obtain an impedance measure which reflects user-perceived cost. Travel time is the measure more frequently used in New Zealand, although other costs are likely to be taken into account. This is reinforced by predictions from models using travel time as the only cost component in traffic assignment leading to predictions which are incompatible with empirical data collected after an improvement has been implemented.

The second implication is that the same user-perceived cost be used as an impedance measure in all travel-demand models. With this requirement, travel demand should be estimated simultaneously for all travel decisions. This does not imply that decisions are made simultaneously, but does imply that decisions are based on a single measure of perceived cost for mode, destination and route.

With regard to resource costs, vehicle operating cost models are required for fuel consumption, maintenance and repair, and use-related depreciation. These should be compatible with the level of detail inherent in the assignment model of the software.

3.3 Summary

Section 3.2 has shown in general terms how user benefits can be estimated for a comprehensive range of urban road improvement schemes. The discussion has served to pinpoint areas which require further research if the economic benefits are to be reliably estimated, following established economic theory. To summarise, the main areas of future research should concentrate on:

i. The development and/or calibration of fuel consumption models appropriate for the level of detail implicit in the traffic models;

ii. Development of a vehicle maintenance and repair model appropriate for urban conditions and possibly tailored to reflect the level of detail in the corresponding traffic models;

iii. Calibration of a perceived user-cost model;

iv. Development of a capability to perform trip distribution, mode choice, and traffic assignment from a single travel-demand model.

It is appropriate at this point to stress that traffic analysis software predicts traffic performance characteristics based on idealised assumptions which only approximate actual traveller behaviour. In the case of lane or route choice, users are assumed to minimise perceived cost of travel. Other travel demand models are regression based and incorporate the assumption that the parameters obtained for a given existing situation are applicable for future improvement schemes. Both these assumptions introduce errors in the predictions obtained which raises questions about using economic analysis alone to determine where funds should be allocated for improving urban networks.

4. DIRECTIONS FOR FUTURE RESEARCH

Research should be continued to achieve the goal of carrying out benefit-cost analyses for urban road improvement schemes using the recommended software. The work required relates to both the traffic software and the economic evaluation procedures.

4.1 Traffic Software

The main requirement for NETSIM is to update the fuel tables so that they reflect the New Zealand vehicle fleet (Section 2.2.1). Some submodels still require calibration and/or validation (Dunn and Tan 1989, 1992).

Now that the TRAF-NETSIM package is available (and a new enhanced version is to be released in 1992, see Section 2.2.1), traffic performance predictions should be compared with those from other models such as SIDRA, and MULATM (now TrafikPlan).

Professor M. A. P. Taylor, the software developer of MULATM (now TrafikPlan), has implemented the analysis for lane choice and priority intersection delay, as incorporated in MULDEL. It is recommended that Transit New Zealand should continue to test and follow developments of TrafikPlan in consultation with Professor Taylor. This should be broadened to include workshops and/or user group meetings.

It is recommended that the motorway traffic simulation program FRESIM be acquired from McTrans (University of Florida) following its release by FHWA, and tested in New Zealand. As noted in Section 2.2.1, FHWA are planning to release new and enhanced versions of their simulation packages, including CORFLO (corridor simulation) and FREEFLO (freeway simulation).

As noted in Section 2.4.2, the program MULDEL was written to provide a means of analysing priority intersection software. A number of desirable enhancements could be incorporated including:

i. Direct consideration of heavy vehicles,

ii. Application to roundabouts.

Also as indicated in Section 2.4.2, the solution algorithm should be replaced by a more efficient approach.

With regard to strategic planning, consideration should be given to developing a capability for combining destination, mode choice, and assignment into a single model, because the sequential approach does not produce consistent results unless an iterative procedure is used to ensure that congestion effects are represented in the travel-demand models. As well as developing algorithms to obtain travel demand predictions, a calibration procedure is required which recognises congestion effects.

4.2 Economic Analysis

The research required to interface economic models with traffic models is summarised in Section 3.3.

4.3 Ongoing Traffic Modelling Research

The reliability of traffic models can be improved with ongoing research and two problems which have received approval for funding at the exploratory level are:

i. Development of a capability to estimate a trip matrix from link traffic count data. If successful, the results from this research will facilitate the problem of estimating a trip matrix for existing traffic conditions, a necessary step in the calibration of a trip distribution model. The approach proposed is described in Fisk and Boyce (1983) and will simultaneously produce a trip matrix together with the impedance parameter.

ii. Formulation and solution of a model which will perform dynamic user-equilibrium traffic assignment. Current assignment models are mostly based on the steady state assumption which implies that, on average, o-d flow rates are constant over the assignment period. This leads to a number of conceptual difficulties, together with errors in the link flow solution, particularly over peak periods when flow rates normally vary considerably.

It is recommended that research continue into the development of link travel time functions for traffic assignment, notably for multi-lane streets and motorways.

5. REFERENCES

Akcelik, R. 1981. Traffic signals: capacity and timing analysis. *Australian Roads Research Board (ARRB) Research Report ARR No. 123.*

Biggs, D., Akcelik, R. 1986. An energy related model of instantaneous fuel consumption. *Traffic Engineering Control 28: 320-325.*

Bone, I.H. 1986. The economic appraisal of roading improvement projects. *Road Research Unit (RRU) Technical Recommendation TR9,* National Roads Board, Wellington.

Cowan, R. 1980. Further results on single lane traffic flow. *Journal of Applied Problems 17: 523-531.*

Dunn, R.C.M. 1989. Strategic planning modelling — with particular reference to EMME/2. *School of Engineering Report No. 465*, Department of Civil Engineering, University of Auckland.

Dunn, R.C.M., Tan, H.H. 1989. Calibration of NETSIM to New Zealand conditions — an executive summary. *School of Engineering Report No. 475*, Department of Civil Engineering, University of Auckland.

Dunn, R.C.M., Tan H.H. 1992. Calibration of NETSIM to New Zealand conditions. *Transit New Zealand Research Report 9.*

FHWA 1989. *TRAF-NETSIM User's Manual.* Federal Highways Administration, Washington DC.

Fisk, C.S. 1987. Urban road traffic models for economic appraisal. Stage III, Report No. 4 — Model assumptions and calibration requirements for NETSIM. Unpublished report for National Roads Board, Road Research Unit (now Transit New Zealand), by Department of Civil Engineering, University of Auckland.

Fisk, C.S. 1988a. Urban road traffic models for economic appraisal: Stage III. *School of Engineering Report No. 452*, Department of Civil Engineering, University of Auckland.

Fisk, C.S. 1988b. On combining maximum entropy trip matrix estimation with user optimal assignment. *Transportation Research 22B(1): 69-79.*

Fisk, C.S. 1989a. Priority intersection capacity - a generalisation of Tanner's formula. *Transportation Research 23B(4): 281-286.*

Fisk, C.S. 1989b. Trip matrix estimation from link traffic counts: the congested network case. *Transportation Research 23B: 331-336.*

Fisk, C.S. 1989c. The Australian Road Research Board instantaneous model of fuel consumption. *Transportation Research 23B(5): 373-376.*

Fisk, C.S. 1989d. Traffic performance characteristics at priority intersections — analysis details. Unpublished report for National Roads Board, Road Research Unit (now Transit New Zealand), by Department of Civil Engineering, University of Auckland.

Fisk, C. S. 1990a. Traffic assignment and the lane choice problem. *Transportation Research 24B(5): 375-389.*

Fisk, C.S. 1990b. Effects of heavy traffic on network congestion. *Transportation Research 24B(5): 391-404.*

Fisk, C.S. 1991a. Traffic performance analysis at roundabouts. *Transportation Research 25B(2/3): 89-102.*

Fisk, C.S. 1991b. Link travel time functions for traffic assignment. *Transportation Research 25B(2/3): 103-113.*

Fisk, C.S., Boyce, D.E. 1983. A note on trip matrix estimation from link traffic count data. *Transportation Research 17B(3): 245-250.*

Fisk, C.S., Dunn, R.C.M. 1986. Urban road traffic models for economic appraisal : Stages I and II. *School of Engineering Report No. 475*, Department of Civil Engineering, University of Auckland.

Fisk, C.S., Dunn, R.C.M. 1987. Urban traffic models for operational analyses and economic appraisals. *New Zealand Roading Symposium 3:* 475-482.

Fisk, C. S., Tan, H. H. 1988. Traffic performance characteristics at priority intersections. Unpublished report for National Roads Board, Road Research Unit (now Transit New Zealand), by Department of Civil Engineering, University of Auckland.

Fisk, C.S., Tan, H.H. 1989. Delay analysis for priority intersections. *Transportation Research 23(B): 453-469.*

Gabites Porter Ltd. 1991. Performance analysis of priority intersections — a practitioner's guide. Unpublished report prepared for Transit New Zealand. 41pp.

INRO Consultants 1986. *EMME/2 User's Manual.*

Kimber, R.M. 1989. Gap acceptance and empiricism in capacity prediction. *Transportation Science 23: 100-111.*

Kimber, R.M., Hollis, E.M. 1979. Traffic queues and delays at road junctions. *TRRL Report LR909*, Transport and Road Research Laboratory, Crowthorne, England.

Little, J.D.C., Kelson, M.D., Gartner, N.H. 1981. MAXBAND: a program for setting signals on arterials and triangular networks. *Transportation Research Record 795: 40-46.*

Rosser, M.S., Milne, A.R. 1981. The application of queueing theory to traffic engineering problems. Report prepared for National Roads Board, Road Research Unit, (now Transit New Zealand), by Department of Theoretical and Applied Mechanics (now Department of Engineering Science), University of Auckland.

Sims, A. G. 1989. *SCATES user manual.* Roads and Traffic Authority NSW.

Tan, H.H. 1989. Simulation of traffic flows on dense urban networks: a study of the calibration requirements of the FHWA-NETSIM model for New Zealand conditions. *School of Engineering Report No. 468*, Department of Civil Engineering, University of Auckland.

Tanner, J.C. 1962. A theoretical analysis of delays at an uncontrolled intersection. *Biometrika 49: 163-170.*

Taylor, M.A.P. 1989. *MULATM User Manual, Version 3.* Department of Civil Engineering, Monash University, Melbourne.

Van Vliet, D. 1982. SATURN - a modern assignment model. *Traffic Engineering Control 23: 578-581.*

Van Zuylen, H.J., Willumsen, L.G. 1980. The most likely trip matrix estimated from traffic counts. *Transportation Research 14B: 281-293.*