A HIERARCHICAL APPROACH TO MODELLING NETWORK FLOWS

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ABSTRACT: *The size and complexity of urban transport systems require that models of such systems be designed to operate within practical and manageable limits on data requirements and computational effort.*

One approach is to use a hierarchy of transport flow models, in which a set of system levels is defined, and particular models used for analysis at each level.

This paper describes the definition of a hierarchy of network flow models, and the classification of various models within this hierarchy. An integrated set of models within the hierarchical framework is described. This set consists of some established models together with some more recent model development. The levels within the hierarchy range from micro-level flow simulation through local area networks to large-scale networks, and strategic land use-transport interaction models. Examples of the use of models for each level are given, and the methods for linking models are defined and explored.

INTRODUCTION

The size and complexity of urban transport systems require that models of such systems should be designed to operate within practical and manageable limits on data requirements and computational effort. At the same time, problems often arise concerning the detailed performance of some components within a network (e.g. a specified link, node, or segment). Possible impacts of policy and operational changes at local and system-wide levels may be of interest, and modelling procedures may be useful tools for these problems. However, individual models may be unable to provide the full range of possibilities and levels of detail to assist in an analysis of this type. Recent interest in modelling energy consumption and emissions in urban traffic systems provides an illuminating example of this type of problem and the difficulties encountered.

Considerable work in research and policy formulation has been reported on the overall consumption of energy by transport (e.g. Lawlor and Brown 1980) and the overall emissions of pollutants from road transport (e.g. Environment Protection Authority, 1979). There has also been much interest in the performance of individual vehicles on the test-bed, or in traffic, as shown in the proceedings of the two joint SAE/ARRB conferences on traffic, energy and emissions held in 1980 and 1982 (ARRB 1980, 1982). However the middle ground between these areas, that of the performance of traffic systems and their component (mixed) traffic streams, has been neglected. It would appear most useful to investigate a methodology for connecting these areas of policy interest and research endeavour within a unified framework.

Urban traffic is an example of a large-scale system involving complex interactions between its components, while itself forming a sub-system within higher-level systems (the urban transport system, and the urban activity system). The interactions between vehicles, traffic streams, controllers, components of other transport sub-systems, and abutting land use activities mean that the overall performance of the traffic system is not a simple function of the performance of its individual components. An interesting example of such effects was described by Gipps (1981) concerning the performance of a traffic stream in which some petrol-driven vehicles were replaced by electric vehicles. Gipps found that for the arterial road studied, the total fuel consumption of the traffic stream could be increased unless the electric vehicles had acceleration and cruising characteristics similar to those of the rest of the traffic.

One approach is to use a hierarchy of models, in which a set of system levels are defined, and particular models used for analysis at each level. If connections for information transfer between levels and models can be established, then an overall systems analysis can be performed. The effects of system or component changes may be investigated over a range of levels of aggregation. Studies at the low (micro) level of the hierarchy may be used to produce submodels for use at higher levels. Conversely higher level network models and land use planning models may be used to generate travel demand data for local area or individual link models.

This paper defines a particular hierarchy of network flow models, and classifies a number of models within this hierarchy. An integrated set of models within the hierarchical framework is described, consisting of some established models together with some more recent model developments. The hierarchy presented here is a development from that suggested by Taylor and Gipps (1982). Changing data requirements and constraints for different model levels within the hierarchy are illustrated, and methods for linking particular model levels are indicated.

A HIERARCHY OF NETWORK FLOW MODELS

The following hierarchy is proposed for transport network systems analysis, from the most detailed (micro-level) to the regional (macro-level):

(a) microscopic simulation of individual units in a traffic stream. This level includes models such as the multi-lane arterial road simulation model MULTSIM (Gipps and Wilson 1980), the rural road simulation model TRARR (Hoban and McLean 1982), and the simulation of pedestrian movements in a plaza (Sands and Ciolek 1979);

(b) macroscopic flow models in which the flow units are assumed to behave in some collective fashion. Examples of such models include the kinetic flow model for a length of road proposed by Herman and Priogine (1979), flow-travel time models (e.g. Davidson 1966), the queue dynamics models for signalised intersections (Stephanopoulos, Michalopoulos and Stephanopoulos 1979), platoon dispersion models (e.g. Seddon 1972), and pedestrian flow models (e.g. Fruin 1971);

(c) simulation models of flows in networks for the optimisation of network performance for fixed route choice preferences. TRANSYT (Vincent, Mitchell and Robertson 1980) is the best known model of this type;

(d) local area network assignment models such as LATM (Taylor 1979), SATURN (Hall, Van Vliet and Willumsen 1980) and CONTRAM (Leonard and Tough 1979), which model route choice through detailed networks representing small parts of an urban area. Also included are pedestrian network flow models such as that devised by Ceder (1970);

(e) large-scale network assignment models such as TRAFIC (Nguyen 1974) or ARRBTRAFIC (Luk, Markarov and Wigan 1979) which may include large sections of an urban area (e.g. Taylor and Anderson 1982) or a complete metropolitan area (e.g. Boyce, Janson and Eash 1981);

(f) large-scale sketch planning models of land use/transport interactions such as TOPAZ (Brotchie, Dickey and Sharpe 1980), which estimate flows between activity centres without explicitly considering the transport network; and

(g) models of regional, national and international flows of people and goods (e.g. Batten 1982).

This hierarchy should not be seen as completely definitive, and there are some overlaps between adjacent levels. The possibilities exist to distinguish levels on the basis of 'study area' or 'study duration', with both the area and the duration typically increasing as one moves from level (a) through to level (g). Study areas increase from a single length of road, to areas of several hectares, to several square kilometres, to entire metropolitan areas, and beyond. Study period durations for microscopic simulations would generally be of the order of an hour or less, increasing to a peak hour (or hours) for the local area models to 24 hour periods for the sketch planning models and perhaps months (or years) for national/international flow models. An analogy might be drawn with the use of a microscope. The lower levels of the hierarchy allow a small area to be studied at high magnification, but as the area of study is increased by reducing the magnification, the finer details disappear.

Constraints on Applying Individual Models

The need for a hierarchical approach to transport network modelling arises from the particular phenomena to be studied, and the data resources and computational effort required to model these phenomena. Significant changes in perspective and planning objectives occur as one moves through the hierarchy. At the lower levels, studies might be required of the effects of traffic management policies. In the middle range of the hierarchy, the planning, location and design of individual traffic generators (e.g. shopping centres) are of interest, while at the higher levels broad land use and transport planning policies, and economic policies, form the objectives.

By way of example, consider a road traffic system. At the microscopic level, detailed study of vehicle progression along a road is of interest, including lane choice, interactions between following vehicles, time spent in queues, and overtaking. At level (b), the macroscopic link flow level, mean travel time, delays and queue lengths on the link are typical dependent variables. Models at level (c) are also concerned with these variables, but also attempt to optimise them across a network. The route choice problem emerges at level (d), at which level network links can still be directly identified with individual roads. Questions arise concerning detailed route choice (e.g. diversions around 'bottlenecks' and the use of 'rat runs') as a function of queuing points, delays and turning manoeuvres at intersections, and the split of traffic between major and local streets. The higher level models (say levels (e) and (f)) are concerned with problems of mode, destination and route choice, plus overall network travel and congestion characteristics. At these levels network links represent only the important parts of the road system (e.g. freeways and major arterial roads), and if the network is diffuse, may use transport 'corridors' to represent groups of parallel roads.

The data requirements for the lower level models (e.g. specification of lane configurations, signal phasings and settings, details of road geometry and alignment, vehicle fleet composition and vehicle performance characteristics) make it impractical to analyse more than a relatively short length of road (perhaps up to 3 km). Computer execution time also limits the scope of a simulation run to a reasonable number of vehicles (perhaps 2000 vehicles for a simulated time period of 15 minutes or less). At higher levels, the specification of the increasing length of road in a network demands less detail for each individual road link. At the local area level (level (d)), individual roads may still be identified in broad terms (e.g. road type, number of lanes, intersection types) but specific details (e.g. regarding alignment) are omitted. At the metropolitan-wide level (level (e)) even fewer details can be given, perhaps only broad identifiers of road type and abutting land use classification. At level (f) only parameters of overall network performance are used, such as mean travel speeds.

OPUS SYSTEM OF NETWORK FLOW MODELS

Continuing work within the CSIRO Division of Building Research has been concerned with the definition and development of various computer based transport network flow models, each of which can be identified with various levels of the hierarchy of models described above. These models are being developed to common standards and are collectively grouped into an urban planning model package called OPUS - Optimal Planning of Urban Systems.

Principal models of the OPUS package include, the multi-lane arterial road simulation model MULTSIM (Gipps and Wilson 1980, Gipps 1982), models concerned with road networks from a local area (suburb) scale (LATM, Local Area Traffic Model, Taylor 1979, 1982a) to the metropolitan scale (OPERA, OPus Equilibrium tRaffic Assignment model, Taylor 1982b) and a comprehensive land use and transport planning model TOPAZ82 (Technique for Optimal Placement of Activities into Zones, Sharpe, Wilson and Pallot, 1982). OPUS includes additional models for energy consumption and pollution emission and dispersion from road networks, URPOL (URban POLlution model, Taylor 1982c) and POLDIF (POLlution DIFfusion model, Anderson 1983, Taylor and Anderson 1982).

Linkages Within the Opus System

The interrelationships between these models can be seen in Figure 1 which depicts their relative positions in the hierarchy and the (two-way) linkages between them. Also indicated is the nature of these linkages i.e. from the top to the bottom, outputs from one model represent inputs (or constraints) to the next. The progression can be viewed as levels of demand information. Output from the upper level model might be a trip demand origin-destination matrix for a large scale urban road network, which would be used as input to the next lower level to yield traffic demands for all roads in a local area network, and finally to the lowest level where the demand would be an estimate of flow on one particular road.

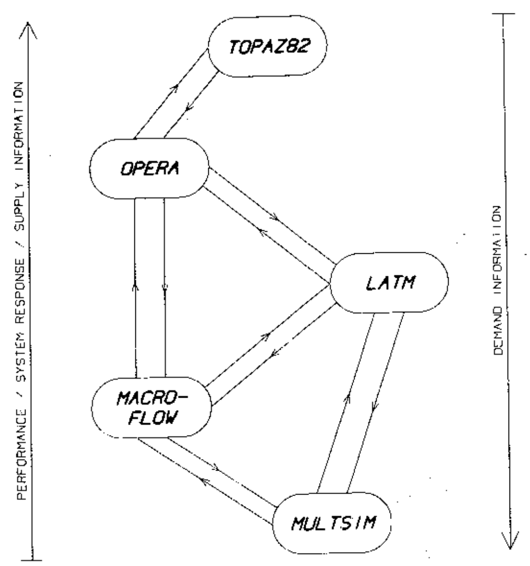

Figure 1. OPUS Network Flow Models System

Reverse linkages or feedback loops operate in the opposite direction where model outputs are interpreted as indicators of performance of the road system, i.e. system response information. These are measures of the adequacy of supply of the individual road or network capacities to cater for the expressed demand. A failure or poor performance of some system response indicator at a lower level would require a reappraisal of upper level modelling efforts with changed or additional input constraints. An example here would be a necessary change to the allocation of land uses in an urban area by the TOPAZ82 model if the OPERA and URPOL models found that pollution levels emitted by traffic assigned in the original allocation were unacceptable.

More specific indications of the types of information flowing between levels of the modelling hierarchy are shown in Figure 2. Here the demand information flowing down the hierarchy is shown to the right of the main diagonal, and the system response or adequacy of supply information flowing up the hierarchy is shown to the left. Thus at the upper levels we have the output from TOPAZ82 in the form of, say, an origin-destination trip demand matrix for a large-scale network, perhaps comprised only of travel corridors, together with overall mean travel costs on the network being supplied to OPERA. In turn OPERA produces sytem response indicators of levels of congestion, aggregate and mean trip costs and energy consumption and pollution emission information for the same network. Areas of poor system performance can be identified and fedback to TOPAZ82 to revise the trip demand matrix and/or the land use allocation plan. Information measures here are expressed in either gross (aggregate) terms or as mean values.

<table>
<tr><th rowspan="2">FROM</th><th colspan="5">TO</th></tr>
<tr><th>TOPAZ82</th><th>OPERA</th><th>LATM</th><th>MACRO-FLOW</th><th>MULTSIM</th></tr>
<tr><td>TOPAZ82</td><td>DEMAND
SUPPLY</td><td>NETWORK TRIP DEMAND OVERALL MEAN TRAVEL COSTS</td><td colspan="3"></td></tr>
<tr><td>OPERA</td><td>CONGESTION LEVELS. TRIP COSTS. TOTAL ENERGY AND EMISSIONS</td><td></td><td>SUB-AREA TRIP DEMANDS TRIP SEGMENT COSTS</td><td>MEAN LINK FLOW RATES AND TRAVEL COSTS</td><td></td></tr>
<tr><td>LATM</td><td></td><td>LINK FLOWS TRAVEL COSTS ENERGY AND EMISSIONS</td><td></td><td colspan="2">MEAN FLOW RATES AND ROAD SECTION TRAVEL TIMES</td></tr>
<tr><td>MACRO-FLOW</td><td></td><td colspan="2">RELATIONS BETWEEN FLOW RATES AND TRAVEL COSTS ENERGY AND EMISSIONS</td><td></td><td>MEAN FLOW RATES AND ROAD SECTION TRAVEL TIMES</td></tr>
<tr><td>MULTSIM</td><td colspan="2"></td><td colspan="2">DETAILED FLOW RATES TRAVEL TIMES ENERGY AND EMISSIONS</td><td>DEMAND
SUPPLY</td></tr>
</table>

Figure 2. Information Transfers Within OPUS Network Flow Models System

At the lower hierarchy levels the emphasis shifts away from aggregate measures towards detailed information for individual roads or sections of a road. Thus from LATM or macro-flow type models, mean traffic flow rates and travel times for individual roads for specific times of day, say, a morning peak hour, are available. MULTSIM can then make use of this information to determine the response of individual vehicles on such a road under the given demand conditions, and output detailed data on individual vehicle travel times, fuel consumption, queuing delay, etc.

At the middle levels of the hierarchy, information flows are concerned with both local area networks and individual roads, but are not concerned with individual vehicles. OPERA can be used to produce a local area trip demand matrix to be used as input to LATM which, in turn, would provide detailed flow and travel cost information for links and intersections within the area. Both OPERA and LATM require expressions indicating how travel costs (or times), energy and emission rates vary on individual road types according to the level of congestion or traffic flow on the road. These expressions can be obtained from macro-flow type models.

The process of feedback of information from lower levels to higher levels and of the varying emphasis of the models can be appreciated by examining the means of calculating fuel consumption in each of the models. MULTSIM uses a very detailed fuel consumption sub-model for individual vehicles derived from Kent, Post and Tomlin's (1982) work on engine mapping. It requires instantaneous estimates of a vehicle's speed and acceleration, updated more than once per second of travel time. When aggregated over all the vehicles on a road it provides a figure which can be compared with that from a suitable fuel consumption sub-model for LATM such as the elemental fuel model (Akcelik, Richardson and Watson 1982) which takes into account vehicles' cruise times and number of stops per road link.

Aggregating over road links yields values to be compared with those of the next hierarchy level model, OPERA, which relates fuel consumed only to mean link travel times ignoring queuing and delay effects at intersections. At the upper level, TOPAZ82 may not even consider vehicle speeds, but simply use some fleet averaged value of litres consumed per 100 km of travel.

EXAMPLES OF MODEL LINKAGES

To illustrate the roles of the various models in the hierarchy and the relationships between them several examples of model use can be presented.

MULTSIM to Macro-Flow Models

Macro-flow models are concerned with the aggregate behaviour of vehicles on a road whereas MULTSIM is concerned with the behaviour of individual vehicles. Anderson (1981) described the use of MULTSIM to model individual vehicles travelling on a multi-lane arterial road and the aggregation of their behaviour to calibrate a macro-flow model.

Herman and Prigogine (1979) postulated a macro-flow model where the average (space mean) speed of moving vehicles, v_r, in a traffic stream is related to the proportion of stopping vehicles, F_s, at any instant by,

$$v_r = v_m (1-F_s)^n \quad (1)$$

where v_m is the average maximum running speed and n is a measure of the 'goodness' of the traffic system, i.e. the standard of the road system and its traffic control devices. Data from roads in London, the U.S.A., and Melbourne indicate that n takes values between 1 and 3. The Melbourne data plotted very closely by slightly above n=1. The average speed of all vehicles, v, is related to the average speed of moving vehicles by,

$$v = v_r \, (1-F_s) \qquad (2)$$

Herman and Prigogine also postulated a relationship between stop fraction, F_s, and concentration k, viz.

$$F_s = (k/k_j)^m \qquad (3)$$

where k_j is the average maximum concentration (at which traffic jams), and m, like n in equation (1), is another measure of quality of the road facilities and traffic control system.

MULTSIM was set up to model a 2.25 km length of a Sydney arterial road during peak hour and to record speeds for individual vehicles and volume, concentration and stop fraction characteristics for the road as a whole. Data covering a large range of F_s values (0 to 0.9) were easily obtained compared with the laborious method of analysing aerial photographs suggested by Herman and Prigogine. Regression analyses on the results of the simulations yielded the following for the speed-stop fraction relation,

$$v_r = 59.7 \, (1-F_s)^{1.37} \qquad (4)$$

and for the stop fraction-concentration expression,

$$F_s = 0.94 \, (k/k_j)^{0.84} \qquad (5)$$

(R^2 values of the log transforms of these equations were 0.90 and 0.89 respectively, and all coefficients were signficant at better than the 5% level).

The value of n (1.37) in equation (4) was within Herman and Prigogine's expected range of 1 to 3 and was close to the end of the range in which earlier Melbourne data were placed, perhaps indicating a general difference between Australian traffic and that of Europe or America. Further, the value of v_m, the average maximum running speed of 59.7 km/h in equation (4) was close to the expected value, the mean of the distribution of drivers' desired speeds, 60 km/h. In equation (5), the value of the coefficient (0.94) was close to the expected value of unity, suggesting that Herman and Prigogine's postulated relationship between stop fraction and concentration holds true.

The combination of equations (1), (2), and (3) with coefficient estimates from (4) and (5) yielded an expression for the classic horse-shoe shaped curve of the speed-volume relationship, viz.

$$q = kv = k_j \, v \, [1 - (v/v_m)^{1/n+1}]^{1/m} \qquad (6)$$

with similar expressions for the speed-concentration and volume-concentration relationships. Curves for these three expressions, provided an excellent fit to the simulation with the curves well representing their idealised forms. As an example, the speed-volume curve is shown in Figure 3.

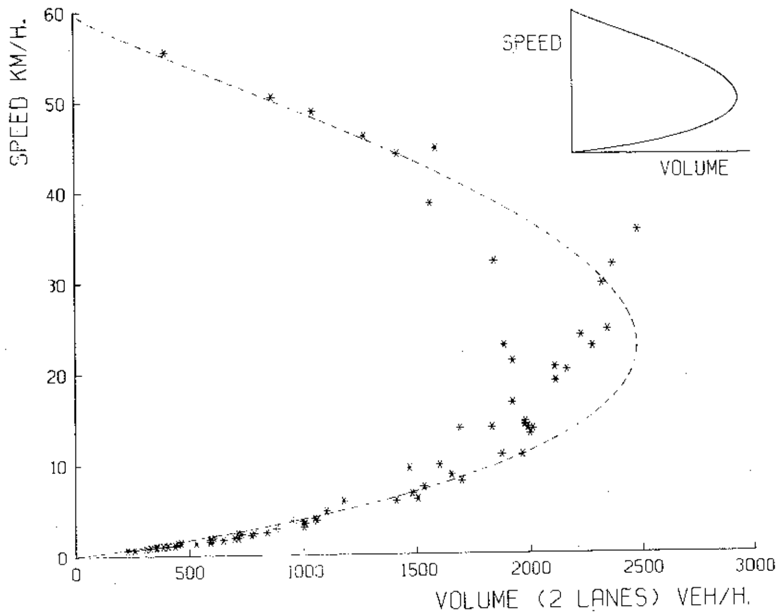

Figure 3. Idealised form and Herman and Prigogine's (1979) Theoretical Speed-Volume Curve Superimposed on Simulated Data Points

Macro-flow to Middle Level Models

Macro-flow models may be used to generate simple expressions relating travel costs, fuel consumption and pollutant emission rates to traffic flows for broad identifiers of road types. Such expressions are required by trip assignment models such as LATM and OPERA. For example the following relation between mean fuel consumption (FC) and unit travel time c (min/km)

$$FC\ (L/100\ km) = 6.64 + 3.59\ c \qquad (7)$$

for the 1978 NSW private vehicle fleet, was derived for use in OPERA (/URPOL) by Taylor and Anderson (1982) from data given by Kent (1980).

For a recent study of pollutant emissions over the Melbourne metropolitan area using OPERA/URPOL, relationships between traffic flow and travel time on various classes of road were needed. In the particular case of four-lane undivided arterial roads, the data and macro-flow relationships given by Beard and McLean (1974) were used to calibrate Davidson congestion functions (Davidson 1966)

$$c = c_0\ (1 + Jq/(s-q)) \qquad (8)$$

where q (veh/h) is a link traffic flow, c (min/km) is a unit travel time, and c_0, J and s are parameters depending on link type and surrounding environment. Separate relationships were estimated for three types of 4-lane road, differentiated by spatial location into 'Inner area', 'Middle suburb' and 'Outer suburb' types after studying the effects of lane use distribution, population density and signalised intersection density in the Beard-McLean model. Table 1 shows the estimated parameters for the three road types, together with the density of signalised intersections (in 1979) for the three types. The relationships are shown in Figure 4. The parameters were found using the method given by Taylor (1977).

TABLE 1
DAVIDSON FUNCTION PARAMETERS FOR THREE CLASSES OF
4-LANE UNDIVIDED ARTERIAL ROADS IN MELBOURNE

PARAMETER	ROAD CLASS		
	INNER AREA	MIDDLE SUBURB	OUTER SUBURB
c_0 (min/km)	1.15	0.85	0.80
J	0.475	0.468	0.486
s (veh/h/lane)	1394	1675	1741
Signalised intersection density (intn./km) (a)	1.97 (0.34)	0.52 (0.07)	0.24 (0.15)

(a) standard error in parenthesis, based on sample counts from maps in Melway (1979).

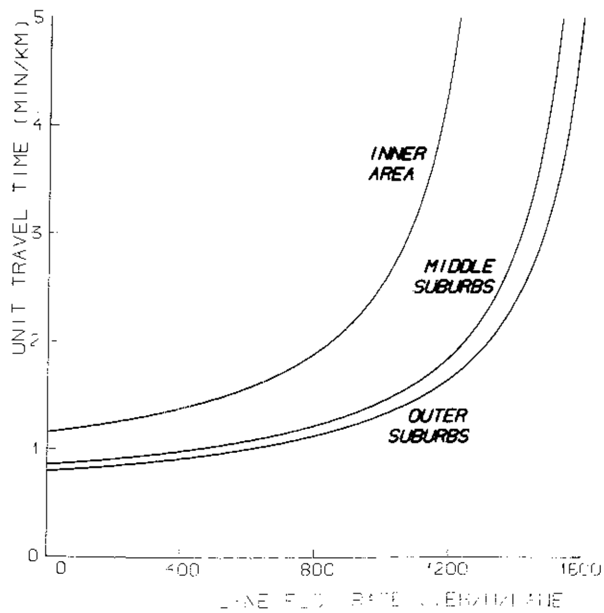

Figure 4. Flow-Travel Time Relationships for Undivided Arterial Roads in Melbourne

OPERA to LATM - Sub-area Trip Demand Estimation

An important linkage within the network flow model hierarchy is that of providing trip demand (origin-destination) data for a local area network (LATM) from a larger-scale network (OPERA). These data may be considered as similar to those from a cordon line survey, with the cordon completely surrounding the local area (see Figure 5). The major complication is that the demand data must indicate the connections of trips entering and leaving the local area. In the field, a 'number-plate' survey might be used to obtain this information. Within the modelling system other methods may be used, involving the estimation of an origin-destination matrix from observed (modelled) link flows. These methods are particularly useful for it is difficult to justify the use of trip distribution models for this application, which involves partial networks and segments of trips. Various solutions to this intriguing problem have been proposed recently, and those due to Van Zuylen and Willumsen (1980) and Le Blanc and Farhangian (1982) are perhaps the best available examples. Van Zuylen and Willumsen used information theory to estimate the demand matrix, while Le Blanc and Farhangian explored an alternative method which used the flows and costs output from an equilibrium assignment to establish a non-linear mathematical programming model for the solution.

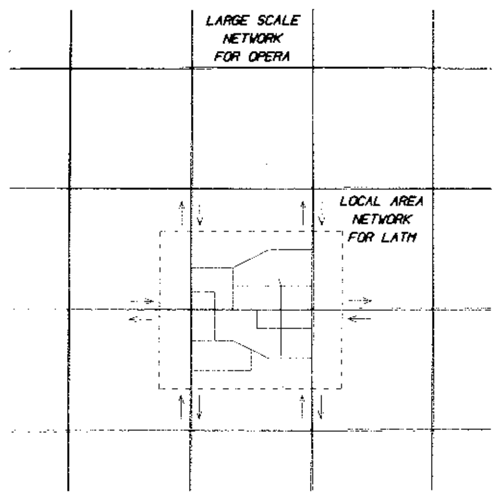

Figure 5. Local Area Network Inside Large-Scale Network

The information theory approach offers some advantages in that:

(a) it can use partial data (i.e. it does not require knowledge of all link flows) to provide estimates, although the estimation procedure is improved if more link flows are available;

(b) it is a general procedure which can use either modelled or observed flows as its inputs; and

(c) it is known to produce unbiased estimates making full use of the available input data.

Currently the Van Zuylen-Willumsen procedure is being implemented to provide this linkage between OPERA and LATM.

Interactions Between OPERA and TOPAZ82

The objective of combining assignment and land use/distribution models is to seek a network equilibirum in which travel demand varies in response to travel conditions on the network. The elements of the interchange are the travel demand origin-destination matrices produced by TOPAZ82, which are used by OPERA to simulate network travel, and the origin-destination trip cost matrix which can be produced by OPERA for use by TOPAZ82. This work is continuing at present, and preliminary results should be available shortly. The feasibility of this interaction has been demonstrated by Luk and Nairn (1980), who are able to locate 'equilibrium' regions in which flows and costs varied up to 10 per cent about the optimum point.

CONCLUSIONS

This paper has identified a series of transport problems requiring solution using network flow models, and has identified a hierarchy of model levels to consider these problems. The hierarchical scheme offers a practical, integrated methodology for studying the effects and influences of changes to network characteristics, travel demands and operating rules at a variety of levels, and for the study and isolation of secondary interactions. Particular models within the hierarchy were described, and communication links between them explored. The integration of models from various levels was shown to offer potential for improved land use/transport/environment impact analysis, by providing mechanisms for connecting micro-level models to general system-wide effects.

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