Extending TRANSIMS Technology to an Integrated Multilevel Representation

Conference or Workshop Item

How to cite:

Serras, Joan (2005). Extending TRANSIMS Technology to an Integrated Multilevel Representation. In: International Conference on Computers in Urban Planning and Urban Management, 29 Jun - 1 Jul 2005, London, UK.

EXTENDING TRANSIMS TECHNOLOGY TO AN INTEGRATED MULTILEVEL REPRESENTATION.

Joan SERRAS
Research Student
Department of Design and Innovation
The Open University
Walton Hall
Milton Keynes MK7 6AA
England
Tel: +44 19 0865 2860
Fax: +44 19 0865 4052
E-mail: j.serras@open.ac.uk

Abstract: New approaches are required to analyse very large land-use transportation systems in which millions of people make millions of trips each day. New computer technology has enabled packages that model very large transportation systems. Some of these models are reviewed and it is concluded that the TRANSIMS system developed at Los Alamos National Laboratory has the best combination of desirable characteristics. All the systems reviewed model links and routes at a single level. Land-use transportation systems are generally multilevel, and the paper reviews a number of approaches to developing multilevel networks with links defined at two or more levels. Of these an approach developed in the nineteen seventies using multidimensional networks has many advantages. The possibility of applying the multilevel representation to TRANSIMS is investigated to produce a land-use transportation modelling system that is unconstrained by size. Such systems could usefully be applied to continents such as Europe, where there are no clear boundaries between cities and urban systems.

Keywords: multilevel hierarchical representation, land-use transportation systems, very large transport simulation, TRANSIMS, MMR.

EXTENDING TRANSIMS TECHNOLOGY TO AN INTEGRATED MULTILEVEL REPRESENTATION.

1 INTRODUCTION

It is evident that nowadays the traffic system of cities requires improvement, to address the traffic jams seen on the orbital roads in European cities like London, Paris and even Barcelona. Thus, new and effective tools are required by traffic planners to improve such systems. One of the tools that has emerged over the last twenty years is road traffic simulation.

For example, the TRANSIMS system developed at Los Alamos in the USA over the past decade is a world leader in providing an integrated land-use transportation dynamical model for large areas with a million or more inhabitants. TRANSIMS uses standard survey data to create synthetic micropopulations, including family structure, to simulate trip making and emergent traffic dynamics.

In common with many other large complex systems, land-use transportation systems are multilevel systems, with emergent phenomena at different levels. For example the European road traffic system has the Paris region as a subsystem, and the Paris region has its arrondissements as sub-sub systems. Currently, systems like TRANSIMS model traffic at a single level, such as routes made up of roads between intersections. It seems essential to extend existing single level modelling systems to multilevel representations in order to model systems with tens or hundreds of millions of people.

The first part of this paper reviews some of these models and concludes that the TRANSIMS system developed at Los Alamos National Laboratory has the best combination of desirable characteristics. In particular the agents in TRANSIMS are synthetic travellers, whose trip generation is simulated based on family structures, giving a close and natural relationship with land-use planning.

The second part of the paper reviews a number of approaches to developing multilevel networks with links defined at two or more hierarchical levels. Of these it is concluded that an approach developed in the nineteen seventies using multidimensional networks has many advantages. These include self-similarity between arbitrary numbers of levels, allowing dynamic traffic flows to aggregate naturally up the hierarchy in a structurally coherent way. Another advantage is that the multidimensional connectivity provides a rich way of analysing the structure of road systems and the way the underlying topology constrains flows and the transmission of traffic congestion.

The third part of the paper investigates the possibility of applying the multilevel representation to the TRANSIMS systems, to produce a land-use transportation modelling system that is unconstrained by size. Such a system could usefully be applied to continents such as Europe, where there are no clear boundaries between cities and urban systems.

The paper reports work on a project in which it is proposed to extend TRANSIMS by adapting it to the multilevel representation. This will allow dynamics to be algebraically integrated at the micro-, meso- and macro-levels.

Applying the representation to a big city starts by defining sets of zones at different levels. At the first level, *N*, is the street. This can be subdivided to building plots at level *N-1*, buildings at level *N-2,* and even rooms at level *N-3*. At level *N+1* are the neighbourhoods, at level *N+2* is the set of district zones (each of them containing the different neighbourhoods in the previous level), and at the top level *N+k*, is just one zone, the city itself. If a larger study area is to be considered, we would have a whole set of *N+k* zones defining (*N+k+1*)-level areas, and so on, extending to the level of counties, countries or even continents.

We suggest how TRANSIMS and the new multi-level representation can be brought together to give new insights into the macro-dynamics of very large road systems such as London, England and even the whole of Europe.

2 MODELLING VERY LARGE TRANSPORTATION SYSTEMS.

2.1 First selection of modelling systems.

One way to define traffic systems is as vehicles with properties such as speed and length, subject to various constrains by the road network (direction of the street, traffic lights, traffic signs…), and interactions with other vehicles. Such types of systems are multi-agent based and they fit very much in the idea of a complex system: we have agents (cars) with different properties which must obey a set of rules in the system giving rise to emergence (traffic jams, agents adapting to the system by choosing a different route…). Also, the level of detail of this approach is quite good (modelling at the level of cars, microscopic simulation) and it will potentially achieve better results in the validation process.

There are two types of microscopic simulations: those that address a small study area (junctions, or just a small portion of a road network) and those designed to study whole urban networks. We will consider the latter. Thus, we will review a number of simulators with these characteristics, namely AIMSUN2, CORSIM, HUTSIM, PARAMICS, TRANSIMS and VISSIM.

2.2 A comparison of the approaches.

A more detailed review is given in order to choose the one which better fits our purposes. The criteria are the size each simulation can address and the level of detail they can achieve.

2.2.1 Size the simulations can address.

As we are interested in simulating very large areas such as Milton Keynes or even London, the system should be able to deal with huge road networks and thus, a very large amount of data. For that reason, implementation of parallel computing should be one of the assets of the chosen simulator. The indicator for that is the size of the network they can model. This information, extracted from (Algers et al., 1997) is summarised below in table 1.

Table 1: Network size limited for the selected software

	Network size limited
AIMSUN2	No
CORSIM	Yes
HUTSIM	Yes
PARAMICS	No
TRANSIMS	No
VISSIM	Yes

2.2.2 Level of detail of the simulations.

Our review of these six modelling systems focuses on the following features:

- the computing facilities needed to build and calibrate the model,
- the methods applied to achieve a realistic simulation,
- the data output (a key feature in model validation) and
- the main applications of the simulation.

While the six selected models share more or less the same characteristics for the first, third and four features, when it comes to the methodology applied for the simulation model definition some differences can be found.

All the models have validated methods for car movement behaviour on roads and they consider most of the Intelligent Transportation System (ITS) measures and have a realistic public transport approach. However, differences can be found while looking at the *level of detail of the simulation*. To quantify the accuracy of the selected models it is important to explain the model which all the traffic simulations are based upon.

Traditionally transport simulations use the 4-step model:

- trip generation within zone,
- trip distribution between origin and destination,
- mode choice and
- assignment of trips to the network.

The trip generation step involves calculating the number of trips getting in and out of the zones by considering their socio-economic, demographic and land-use data.

In the trip distribution step the generated trips are coupled together between the different zones; that is, each trip will be assigned an origin and a destination according to travel time and/or cost.

In the mode choice a mode (walk, car, bus …) is determined for each trip.

Once the origin and destination demand has been determined it is assigned to the network in the final step.

Some feedback procedures are present in the model from the fourth step to either the second or the third.

The unit of analysis used in the model is of crucial relevance. Some models have zones as the least aggregate unit while others have individual travellers.

TRANSIMS's unit of analysis is a person from the so called synthetic population whereas for the rest of the simulations considered the unit is the zone. This very feature defines a series of differences between TRANSIMS and the rest of the simulation systems reviewed:

- TRANSIMS is a disaggregate model (individual analysis) whereas the rest of the models are aggregate (zonal analysis).
- TRANSIMS is activity based whereas the approach from the rest is trip based.
- TRANSIMS allows trip chaining (all the different trips of any synthetic traveller can be traced) whereas the rest of the models don't.

As the level of detail increases, the simulation will achieve a more realistic behaviour therefore TRANSIMS is the best in that sense. Moreover innumerable outcomes arise from this approach such as having the possibility to know broadly at any time where a certain citizen is within the city.

2.2.3 Results of the comparison.

As a result of the comparison among the selected software systems according to the chosen criteria TRANSIMS is selected as its level of accuracy is better than the others and it can model networks of any size as parallel computing can be performed.

3 MULTILEVEL APPROACHES TO MODELLING VERY LARGE NETWORKS.

The concept of hierarchies is not new in the area of transportation; many theories have been developed to represent such systems hierarchically.

Traditionally roads are classified by the level of the areas they serve. For example, local roads serving small areas are defined to be 'minor roads', while roads serving large areas such as motorways are considered to be 'major' roads. In the United Kingdom there are the classes: Motorways (M), A-roads, B-roads, C-roads, and unclassified.

Most of the descriptions approach the idea of classifying the resources of the transport network into different levels according to different kind of parameters, *e.g.*, functionality of the roads (traffic volume, speed …).

Moreover Marshall has given a classification based on arteriality and access constraint (Marshall, 2005).

Other structural stratification is defined according to the traffic flow. It has been claimed that such hierarchy emerges from the network itself rather than being defined by urban planners (Levinson, 2004).

On the other hand, a different concept of road network hierarchies has been developed on the field of traffic simulation. This consists in organising the road urban network data provided from digital maps in Geographical Information Systems (GIS) in a multilevel representation of links and nodes. The key objective for designing such a structure is to reduce the amount of data to be processed while finding shortest paths between origins and destinations: the larger the system is, the faster the algorithm will perform.

This kind of representation has not only been applied in the transport field but in other fields such as network communications (mobile ad hoc networks – MANET, Sucec and Marsic, 2004) and in graph systems in general (Shapiro et al., 1992 and Tan et al., 2003).

Although many of these representations share the same basic idea (graph partitioning) there are still some differences between them. Our aim will be to choose the most suitable, always keeping in mind its latter integration into TRANSIMS. The following are considered to be some of the most relevant in the field:

3.1 HiTi (Hierarchical mulTi) graph model (Jung and Pramanik, 1996).

This approach enables the representation to have as many levels as the user wishes. To build it, a bottom up approach is considered having the original road network at the lowest level. From there, the next level up is defined by the set of so-called Component Road Maps (CROMs), subgraphs defined by the user which cover the whole network. There is no rule for defining the CROMs. Once these CROMs are defined two kind of connectivity arise: between-connections (edges between the boundary nodes of the CROMs) and within-connections (the shortest path between each pair of boundary nodes of each CROM). The fact that the cost of edges might change at some point in time is not considered in the routing algorithm developed.

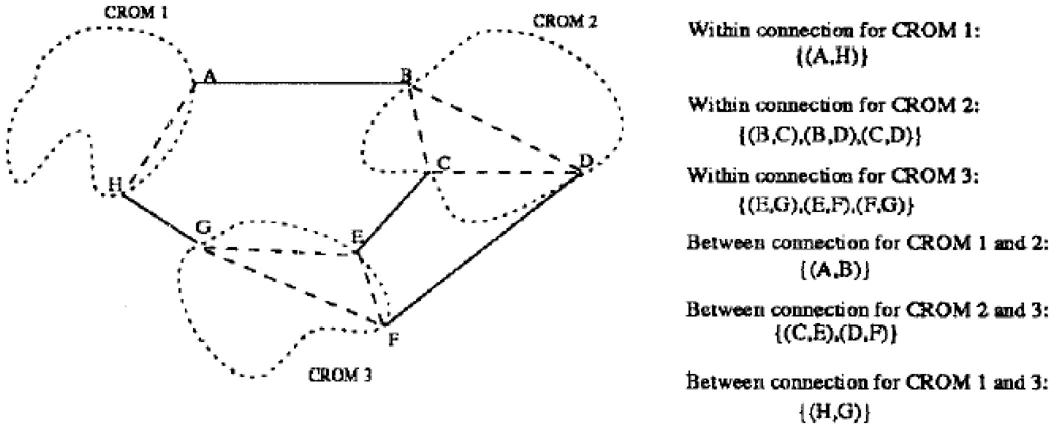

Figure 1: Examples of within and between connection of CROMs from Jung and Pramanik (1996).

3.2 Hierarchical encoded path view (HEPV) (Jing et al., 1998).

Again this representation can have as many levels as the size of the study network area requires. The hierarchical structure is defined with a bottom up approach, with each level being composed by different fragments (set of nodes and links). The rule to define the fragment partition at each level is for each one of them to have the same number of nodes so as to achieve minimum total pre-computation, and an automatic clustering technique is applied. The links at any level different from the lowest one (original network) is again the shortest path between the boundary nodes of the fragment at the lowest level (original road network). The dynamic behaviour of the link costs is taken into account; moreover, extra information is passed to the representation to ease such task with the Hierarchical Path Views (HPV). Optimal shortest route is found with this representation in the sense that the shortest route found using HEPV is the same one as the one found using Dijkstra's algorithm (Dijkstra, 1959) in the original network itself.

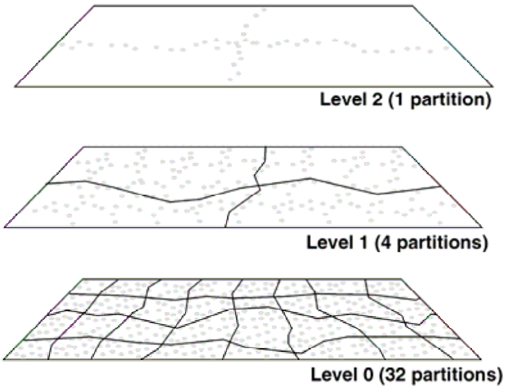

Figure 2: Creating the hierarchy through fragmentation from Jing et al. (1998).

3.3 Hierarchical wayfinding (Car et al., 2001).

This representation has 3 set up levels: 0-level (motorways), 1-level (main roads) and 2-level (local roads). The multilevel structure is not been previously computed, and the method used consists in finding an approximation of the shortest path starting at both origin and destination nodes (bidirectional search) using Dijkstra's algorithm, then when any of the routes found in any side leads to a node with access to the next level, a subgraph for that level is created (bottom up approach) and so on until the routes meet. Such algorithm is said to create subgraphs *on-the-fly*. Experiments done with this algorithm find longer paths than the true shortest paths. The inaccuracy of those paths increases as higher levels are reached.

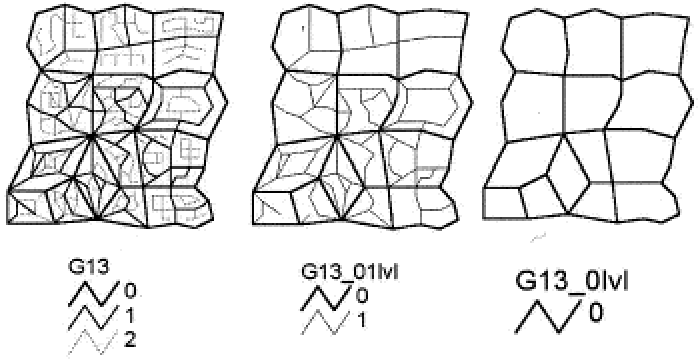

Figure 3: A graph with three hierarchical levels: (left) full graph containing all nodes and edges (lowest level); (middle) a subgraph containing only two levels of detail; (right) the smallest subgraph containing only the highest level (0-level) from Car et al. (2001).

3.4 Heuristic-hierarchical algorithm (Jagadeesh and Srikanthan, 2002).

In this algorithm the road network is first organised according to the designer as a two-layer hierarchy. The bottom layer is composed of the original study road network while the top layer is conformed by the major roads within the study area. These two layers are connected via entry/exit nodes (E-nodes). The heuristic node promotion technique is applied when looking for the shortest path between two nodes so as to save the maximum number of shortest path calculations between the origin and its nearest E-nodes and between the destination and its nearest E-nodes. The results of such implementation are very small differences between the routes found using the node promotion hierarchical algorithm and Dijkstra’s algorithm to the original road network.

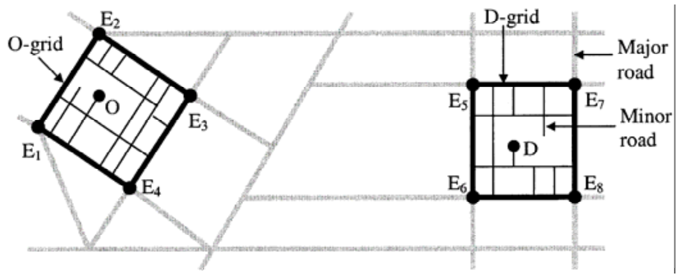

Figure 4: Illustration of two-layer hierarchy from Jagadeesh and Srikanthan (2002).

3.5 Hierarchical Algorithm (HA) (Chou et al., 1998).

The HA is designed to find the shortest path in a road network defined in two levels according to the natural hierarchy of the roads themselves. Thus, the macronetwork is first defined (top down approach) with macronodes and macroarcs: the macronodes (or gateways) are the different entries and exits from the macroarcs which are the different highways and freeways distrubuted in the study area; the macroarcs are considered to be micropaths. The microsubnetwork is the network enclosed by the different macroarcs. Two algorithms are described: nearest HA and best HA which are based in calculations of the shortest path between O/D nodes and the macronodes between them. This is done in the run-time process (no preprocessing). On-line calculations taking into account the varying behaviour of the costs of the links are implemented.

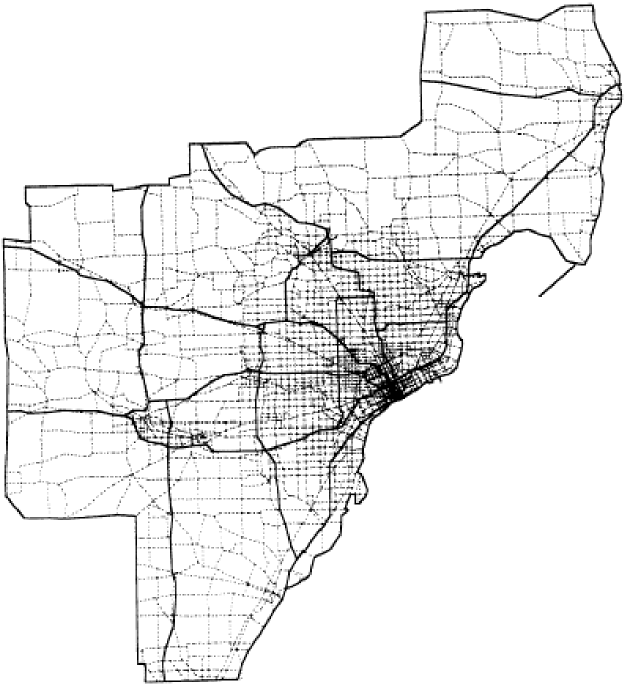

Figure 5: The modified two-level SE Michigan road network from Chou et al. (1998).

3.6 2-level representation using recursive progression (RP) (Awasthi et al., 2004).

The main contribution from this representation is the two clustering techniques applied to partition the graph into two levels. RP-1 and RP-2 are algorithms based on the concept of density. RP-1 is found to be more efficient in terms of homogeneity at the expense of time computation. Such algorithm looks for the optimal distribution of subgraphs such that the connectivity between them is minimal (minimum number of boundary nodes per subgraph). A routing algorithm is developed using statistical analysis to calculate the shortest path considering the dynamic behaviour of links in a road network.

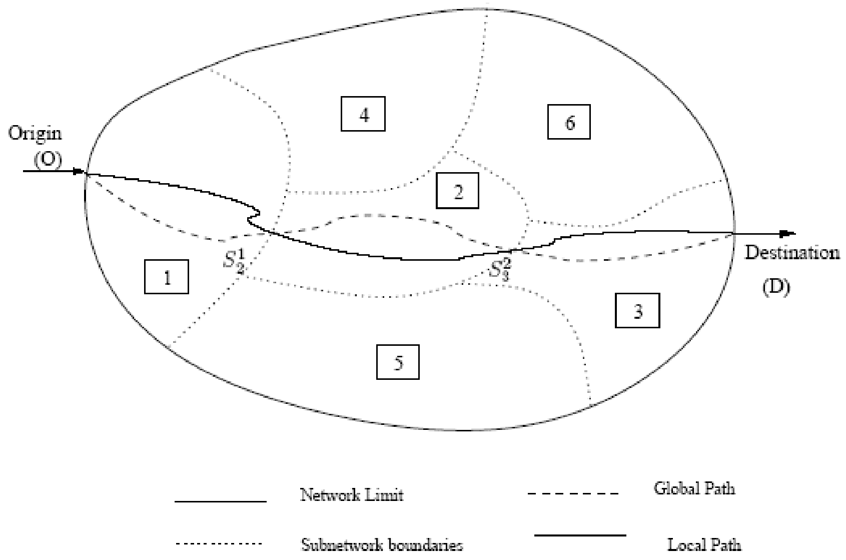

Figure 6: Route guidance approach from Awasthi et al. (2004).

3.7 Multidimensional Multilevel Representation (MMR) (Johnson 1981, 1986, 1991)

This hierarchical representation has no limits in terms of number of levels. The base level is the original road network. Higher levels are defined by nested sets of hierarchical zones by a bottom up approach that takes administrative boundaries into account. Each zone at any level defines a set of *boundary nodes*, which are places where vehicles can travel across the boundary. These boundary nodes define a set of higher level links across the zone. These more abstract higher level links are composed of all the possible paths to go between their boundary nodes at the base level (see Section 4).

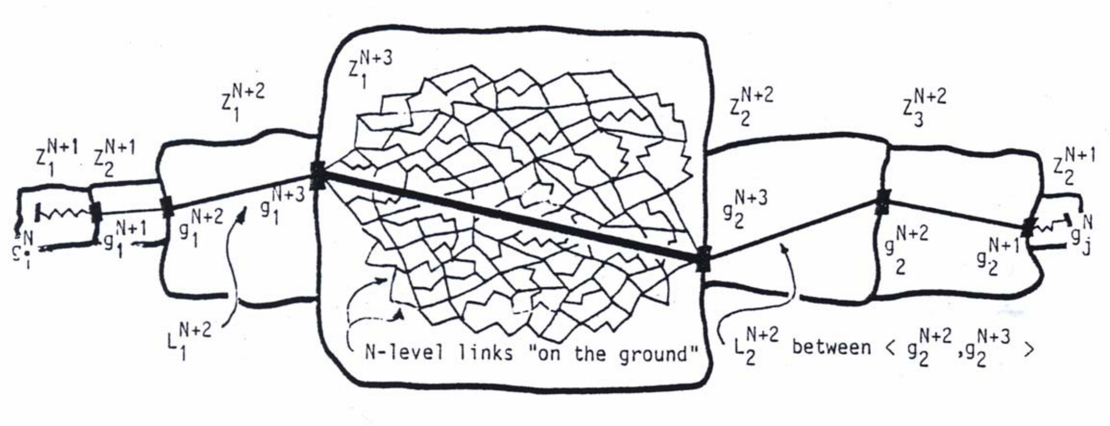

Figure 7: A hierarchical route across hierarchical zones between two nodes from Johnson (1981).

3.8 Comparison.

Table 2 below summarises the different hierarchical models considered:

As stated previously, the main reason for comparison between all these models is to choose the one which will achieve a better performance when applied to a traffic simulation of a very large system.

One of the factors to determine the choice is the amount of precomputing needed by the models. This is important as storing precomputed routes for each level will improve the computation time considerably. Another factor which will help improve the computation time is the number of levels one can define in the model; this will allow the routing methods (assuming precomputing is done) to save more data processing as higher levels are achieved. The third factor considered is the dynamic link behaviour which is a desired condition as the representation will have to deal with the simulation. The last one is the accuracy of the shortest routes found using the different routing methods, this will be called optimality.

Table 2: Summary of models according to chosen features.

	Number of levels	Precomputing	Dynamic link behaviour	Optimality
HiTi graph model	No limit	Yes	No	Yes
HEPV	No limit	Yes	Yes	Yes
Hierarchical wayfinding	3	No	No	No
Heuristic-hierarchical algorithm	2	No	No	No
HA	2	No	Yes	No
2-level representation using RP	2	No	Yes	Yes
MMR	No limit	Yes	Yes	Yes

Then, according to the considerations previously made, the two best hierarchical models are the HEPV and the MMR. However, HEPV's formulation stores just the shortest paths in the so called FPVs (flat paths view) whereas MMR stores a set of N-shortest routes in the level links. This property will allow for a more efficient shortest path algorithm calculation when the link update process takes place when the model is running in parallel with the simulation.

Thus, in our research the MMR is the chosen model to implement the multilevel representation.

4 MULTILEVEL MULTIDIMENSIONAL REPRESENTATION (MMR).

The initial point to start defining the MMR is the original road network, as a set of links and nodes 'on the ground'.[1] Given this, the next step is to construct a set of *hierarchical zones*. A zone is a contiguous area on the map. For every zone we create a node where a road crosses its boundary, as shown in Figure 8(a).

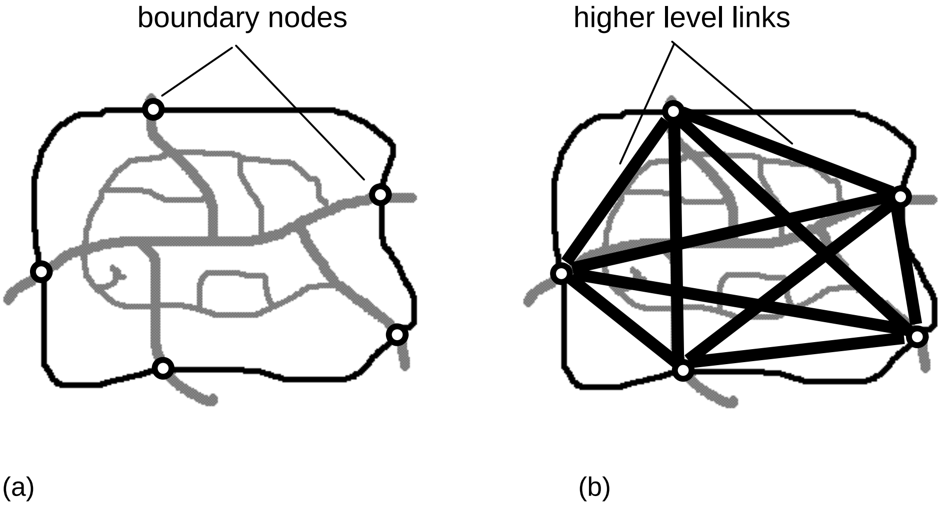

Figure 8: Boundary nodes and higher level links between boundary nodes.

The higher level links are created between each pair of boundary nodes for the zone, representing the possibility of travelling across the zone (Fig. 8(b)). This higher level link represents *all* the routes between the boundary zones that carry traffic. Thus the higher level link has a *distribution* of travel times associated with it, these being the travel times over the routes 'on the ground'.

Let the lowest level zones exist at Level 1. Level 2 zones are formed from sets of contiguous Level-1 zones, as shown in Figure 9. This too has boundary nodes where roads cross the boundary, and these can be used to form links at the next level. This link represents all the routes made up of Level-2 links between the boundary nodes.

---

[1] The MMR actually allows us to go below this level, down the plots of land with buildings, or even rooms, but for simplicity of exposition we will stay at the level of roads and intersections.

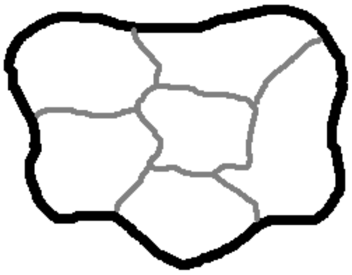

Figure 9: A level-2 zone formed from a set of Level-1 zones

Continuing in this way, a *hierarchical sequence of zones* can be defined as shown in equation 1 below:

$$Z^{N-i} \quad \Lambda \quad Z^{N-1} \rightarrow Z^{N} \rightarrow Z^{N+1} \rightarrow Z^{N+2} \quad \Lambda \quad Z^{N+k-1} \rightarrow Z^{N+k} \qquad (1)$$

Higher level links are defined using the higher level zones, and higher level routes are defined to be sequences of contiguous links between boundary nodes. This method of constructing higher level links works in general between Level-N and Level-N+1. In this sense the representation is *self-similar* between levels.

One approach to defining the hierarchical zones is to partition the network. There are various techniques to partition a graph into subgraphs, however at the moment we'll just stick to the natural distribution of the administrative boundaries at each level (neighbourhoods, districts, cities, counties …).

Note that this representation is based on the road network, and in this particular case, the base level Z^N is defined by the links and nodes from the digital maps.

Summarising, the main properties of the MMR are the following:

- Model of the road network in a holistic way (it includes all the smallest level links for we want no piece of road to be left out).
- It captures the dynamics of road traffic: the micro-dynamics (shockwaves, traffic in links, junctions) and the macro-dynamics (transmission of congestion as it aggregates bottom-up dynamics), hence providing a suitable framework for Q-analysis (Johnson, 1981) which links to the idea of dynamic flow distribution.
- It distributes computation and data naturally across the different administrative levels.

5 INTEGRATING THE MMR TO TRANSIMS.

TRANSIMS is a multi-agent traffic simulation based on four modules: the population and activity generator, the router, the micro-simulation and the emissions estimator.

The first module creates a synthetic population with similar characteristics than the one from the study area and allocates each single unit (habitant of the population) in the previously defined urban network with similar distribution than the one from the study area. This is done according to the collected census data. Once the synthetic population is generated the same module assigns daily activity plans to each one of its components using some data from a survey done to a portion of the population (extrapolation techniques used in order to achieve it).

The router assigns the locations for each one of the plans in the urban area (previously defined with the entire road network and all the activity locations) and chooses the modes (walk, car, transit...).

Finally, the micro-simulation executes all the activity plans together re-routing the ones which can't be executed due to the traffic conditions (a traveller may want to pass through a link which may be congested after previously executing some plans). This is the roll of the feedback, another important feature of the TRANSIMS program.

Once all the daily plans of each component of the synthetic population are simulated, we can get an estimation of the emissions in the study area with the emissions estimation module.

The integration of the MMR in TRANSIMS will affect the router module in terms of computation time as the simulation will achieve a better performance. The first interaction of the MMR with TRANSIMS will happen every time a request for the best route from a synthetic traveller to achieve his activity plan is being made in TRANSIMS. At this point, the hierarchical routing algorithm will start working providing the traveller with the optimal route. The MMR then will work in parallel with TRANSIMS and thus, an efficient way to store all the data from the different levels is desired so that TRANSIMS can access them easily.

Looking at TRANSIMS and the way the router works, we realise that the different modes in the program are represented with different layers (see figure 8 below) providing a more detailed description of each particular mode (transit network, walk network and street network). I believe such a structure will allow for an easier integration of the MMR into TRANSIMS as the routines for changing from layer to layer have been already defined and introduction of more layers may have been taken into account. However, this needs to be further investigated.

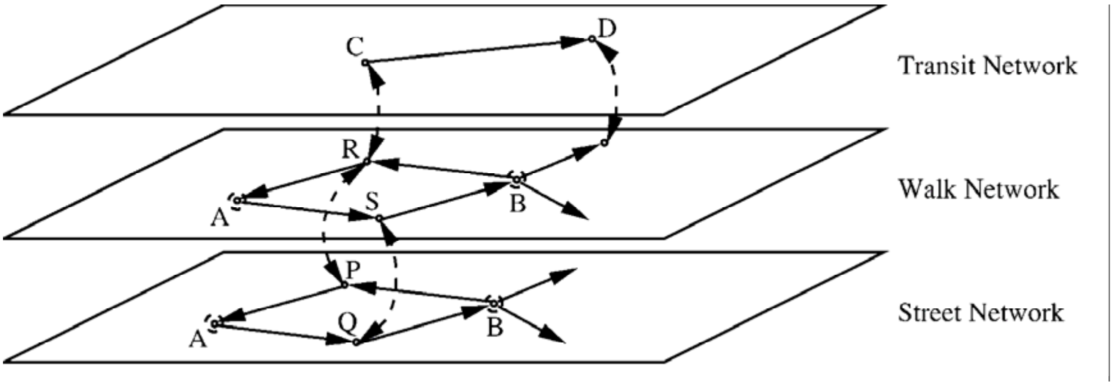

Figure 8: Conceptual diagram of the Planner Network. Parking accessories are in the Street Network, activity locations in the Walk Network, and transit stops in the Transit Networks from Barrett et al. (1999).

On top of this, when the links' costs are updated in TRANSIMS, they will do so automatically in the MMR for each of the affected level links at any level. This will allow for a more efficient updating procedure as it won't be necessary to recalculate again the shortest routes for the affected zones using Dijkstra's algorithm as it will be just a matter of reordering the routes in the level link so that the shortest one will be ready to be picked.

6 CONCLUSIONS AND FURTHER WORK.

In this paper we have chosen a modelling system according to the level of detail of the simulation or, to put it in different words, according to the precision on the agent definition in their multi-agent approach (microscopic system); and by considering those able to model large urban areas. TRANSIMS is chosen as its accuracy in the model is better (the agents are not the cars but the people).

Similarly, a hierarchical representation is selected as being the one which will give the best performance when coupled with TRANSIMS. The MMR is finally chosen considering the number of levels the model can have, the need for precomputing to save some data processing in later stages when the model is running in parallel with the simulation, the dynamic behaviour from the links in terms of variable cost, and the optimality of the route found.

Finally, one way to couple TRANSIMS and the MMR has been suggested, taking advantage of the resources that already exist in TRANSIMS (presence of different layers representing and combining different travel modes).

Further work will consist in investigating TRANSIMS' router module further to determine a precise way to integrate the MMR efficiently getting both packages to work naturally when exchanging data (route request, route provision and link travel times updates). Experimental results are expected from the experiments done with this framework in a big study area such as Milton Keynes (200.000 habitants).

ACKNOWLEDGEMENTS

I'd like to thank Prof. Jeffrey Johnson for his continuous guidance and support and Prof. Antoine G. Hobeika who gave us some ideas during our stay in Virginia Tech in 2004.

REFERENCES

Algers S., Bernauer E., Breheret L., Boero M., Di Taranto C., Dougherty M., Fox K. and Gabard J.F. (1997) **Smartest, Deliverable 3**, Appendix D.

Awasthi A., Parent M. and Proth J. (2004) Decomposition of an urban network for implementing a hierarchical route guidance system, **Proceedings 11th World Congress on ITS** , Nagoya, Japan, October 2004.

Barrett C.L. et Al. (1999) TRansportation ANalysis SIMulation System (TRANSIMS), Version TRANSIMS-LANL-1.0, Vol. 2, Part 1. LA-UR 99-1658, Los Alamos, NM, USA.

Car A., Taylor G. and Brunsdon C. (2001) An analysis of the performance of a hierarchical wayfinding computational model using synthetic graphs, **Computers, Environment and Urban Systems, Vol. 25**, 69-88.

Chou Y., Romeijn H.E. and Smith R.L. (1998) Approximating Shortest Paths in Large-Scale Networks with an Application to Intelligent Transportation Systems, **INFORMS Journal on Computing, Vol. 10**, No. 2, 163-179.

Dijkstra W. (1959) A Note on Two Problems in Connection with Graphs, **Numer. Math., Vol. 1**, 269-271.

Jagadeesh G.R. and Srikanthan T. (2002) Heuristic Techniques for Accelerating Hierarchical Routing on Road Networks, **IEEE Transactions on Intelligent Transportation Systems, Vol. 3**, No. 4, 301-309.

Jing N., Huang Y. and Rundensteiner E.A. (1998) Hierarchical Encoded Path Views for Path Query Processing: An Optimal Model and Its Performance Evaluation, **IEEE Transactions on Knowledge and Data Engineering, Vol. 10**, No. 3, 409-432.

Johnson, J.H. (1981) The Q-analysis of road traffic systems, **Environment and Planning B, Vol. 8**, 141-189.

Johnson, J.H. (1986) Hierarchical backcloth - traffic simulation, **Environment and Planning B: Planning and Design**, 415-436.

Johnson, J.H. (1991) The dynamics of large complex road systems, **Transport Planning and Control**, 165-186.

Jung S. and Pramanik S. (1996) HiTi Graph Model of Topographical Road Maps in Navigation Systems. **Proceedings IEEE 12th International Conference on Data Engineering**, Los Angeles, USA, 1996.

Marshall, S. (2005) Transit-oriented hierarchy: Towards an integrated transport network structure. **Proceedings 37th UTSG Annual Conference**, Centre for Transport and Society, Bristol, England, 5-7, January 2005.

Shapiro J., Waxman J. and Nir D. (1992) Level graphs and approximate shortest path algorithms, **Networks 22**, No. 7, 691-717.

Sucec J. and Marsic I. (2004) Hierarchical Routing Overhead in Mobile Ad Hoc Networks, **IEEE Transactions on Mobile Computing, Vol. 3**, No. 1, 46-56.

Tan G., Han X. and Gao W. (2003) Network-Tree Model and Shortest Path Algorithm, **Lecture Notes in Computer Science, Vol. 2659**, 537-547.

Yerra, B. and Levinson, D. (2004) The Emergence of Hierarchy in Transportation Networks, **Western Regional Association Meeting**, Rio Rico, AZ, USA, February 2004.