Design of Road Networks

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Abstract

One of the major problems faced by residents of Auckland is traffic, especially traffic congestion. The process of designing road networks and improvements that help alleviate congestion and shorten travel times is a difficult task, but one that can be addressed through the use of traffic models and traffic assignment techniques.

This project focuses on the use of these techniques, and in particular applies them to the road network north of Auckland in order to analyse the performance of the network on public holidays. On public holidays a large increase in demand for travel north causes major congestion on the two primary routes leading north, being state highways 1 and 16, with the majority of travellers choosing the highly congested state highway 1 over the less congested state highway 16.

Through the application of traffic modelling techniques and by comparisons between model results and real world traffic flows, we make conclusions about the performance of the road network north of Auckland in regards to the goals of the user and of network planners, and evaluate potential solutions for reducing congestion on state highway 1.

Key words: Road networks, network design, traffic prediction, traffic assignment, user equilibrium system equilibrium.

1 Introduction

One of the major problems faced by residents of Auckland is traffic, especially traffic congestion. The process of designing road networks and improvements that help alleviate congestion and shorten travel times is a difficult task, but through the use of traffic models and traffic assignment techniques we can begin to address the issues surrounding the design of transportation networks.

Of particular importance are the times of peak demand where a large amount of traffic is placed on the road network, such as during special events or holidays. These spikes in demand cause heavy congestion on roads which do not have the capacity required to facilitate demand in peak periods.

An example of such a scenario is the situation of the state highways north of Auckland, where the large surge of demand on long weekends from people wishing to travel north to Warkworth, Wellsford and further. This peak demand causes major congestion on the two primary routes leading north, being state highways 1 and 16, henceforth referred to as SH1 and SH16 respectively. In particular congestion is highest on SH1, with the majority of travellers choosing it over the longer but less congested SH16 (Traffic count data, 2008).

It is the opinion of the New Zealand Transport Agency (NZTA) that the usage of SH16 during these times is not sufficiently high given the heavy congestion present on SH1, and as such NZTA often runs advertisements on radio and in print in the days prior to a long weekend encouraging motorists to travel on the less congested alternative of SH16 in order to reduce the congestion experienced on SH1.

The focus of this project was to investigate the performance of SH1 and SH16 in these heavy congestion scenarios, which was accomplished through the application of traffic forecasting models and techniques; these methods allow a transportation network to be evaluated under particular demand loads by predicting the relative usage of the elements of the network. For this project these elements are the roads and highways of the network, but models may be extended to include aspects such as rail and ferry routes.

By predicting road usage under different assumptions about user behaviour and comparing the resulting traffic flows against observed real world flows, we can make conclusions about the performance of the road network north of Auckland in regards to the goals of the user and of the network planners.

2 Traffic Forecasting

The goal of traffic forecasting is to predict the relative usage of elements of a transport network, typically roads, given a specified demand on the network. This is achieved through forming a computer model that represents the transport network, and using special algorithms to accurately map the demand on the system into the resulting flows that would be observed in a real-world situation.

The ability for transportation scenarios to be modelled and performance evaluated has many practical applications. Applications include: analyzing user behaviour; evaluating performance of current systems under current or future demand; or evaluating modifications to transport infrastructure or policy and quantifiably assessing the relative performance of the changes.

2.1 Aspects of the Computer Model

2.1.1 Network

The main component of the computer model is the transportation network itself. The transportation network is represented in the model by a directed graph, where the nodes of the graph represent locations such as intersections and suburbs. The arcs in the graph represent a mode of travel between two locations, and are commonly referred to as links in transport literature. For this project these links will represent roads, but transportation models are commonly extended to include other modes of transport such as rail or ferry when such modes are deemed important.

Formally, the network is represented by a graph $G = (V, A)$ where $V = \{1, \dots, n\}$ denotes the n nodes of the network and $A \subseteq V \times V$ is the set of directed arcs between nodes.

2.1.2 Link Cost

In addition to representing the physical layout of the transport network and the modes of transport between locations, the model must also consider the cost of travel on each of the arcs in the network. This cost of travel will form the basis for user decision making when solving.

To model this we associate a cost function c_a for each arc $a \in A$ in the network reflecting the cost of travel. For a typical network of roads the cost of travelling on a particular road is given by the travel time. This is generally given as a function of the traffic quantity on the road, denoted by v_a.

2.1.3 Demand

As stated at the beginning of section 2 the goal of traffic forecasting is to predict the usage of parts of a transport network under a particular loading; this loading is the demand of the road users and forms a large part of the modelling process.

Demand in this case is stated at a basic level, where for pairs of locations we state the quantity of people who wish to travel from the first location to the second. Generally a set of special nodes called centroids are selected from or added to the model, these centroids represent particular areas of the network, and are the primary endpoints for the set of demands in the model.

The pairs of locations used in the statement of demand are termed origin-destination (OD) pairs, the set of which we denote by W. For each $w \in W$ we have an associated demand between the locations of d_w. Of note is that this formulation is independent of the links in the network, in that it does not state or restrict the links that will be used to meet the demand. The decisions of what links will be used are instead carried out by the solver.

2.2 The Four Stage Modelling Process

Traditionally when attempting to model a transportation scenario a four-stage process is followed. Initially developed during the 1950s for use in the Chicago Area Transport Study (Black, 1990), the four-stage process is the basis for most modern techniques (Ortuzar & Willumsen, 2001).

The four stages are *trip generation*, where demand is estimated between regions of the model. Region-based demand is then broken down into specific origin-destination demand pairs in the *trip distribution* stage. The modes of transport to be used for each origin-destination pair is then modelled in the *mode choice* phase. In the final stage the demand for each origin-destination pair is assigned to routes in the network via a route selection algorithm, resulting in a set of traffic flows for every link in the network. These results may then be fed back into earlier stages to refine the input parameters used.

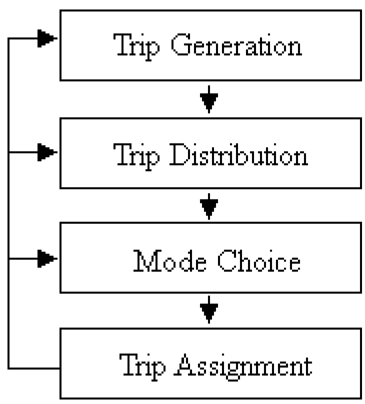

Figure 1. The four stage modelling process

2.2.1 Trip Generation

Trip generation is the initial stage, and involves examining the regions of interest and for each region determining the frequency of trips into and out of the region. This information is based on the aggregate data of the particular region, with characteristics such as population size, population demographics, and economic factors taken into consideration.

2.2.2 Trip Distribution

Trip distribution takes the inter-region demands produced by the trip generation stage and refines the demand locations to produce origin-destination pairs for use in solving. This is accomplished by considering the density of population and industry within the zone, and proportionally assigning demand endpoints in line with these densities.

2.2.3 Mode Choice

The mode choice stage takes the demand quantities for each origin-destination pair found in the trip distribution stage and decides what fractions will be satisfied by each mode of transportation, commonly automotive, bus, rail, or ferry.

2.2.4 Trip Assignment

Trip assignment is the fourth stage in the four stage transportation modelling process. In this stage the completed demand information from previous stages is mapped onto the transportation network to get the resultant traffic flows.

The main aspect of trip assignment is modelling what routes users take through the network to reach their destinations. This is a complex task, requiring careful formulation of user behaviour and goals such that the results produced accurately reflect the desired behaviour.

2.2.5 Flow back

After completing any of the four stages of the modelling process, results from that stage may be used to refine or recalibrate the input parameters or methods of previous stages. An example of such a flow back of information is from the trip assignment phase back to the mode choice phase. After the trip assignment phase has run, the travel times and other costs of the links in the network can be determined, these updated costs may result in people choosing alternative modes of transport.

3 Traffic Assignment

The focus of this project is on the traffic (or trip) assignment stage of the typical four-stage modelling process. By focusing on this stage of the modelling process we hope to be able to analyze the situation of SH1 and SH16 and the choices users make, including reasoning about the causes of such choices, in addition to drawing conclusions about the state of the northern highway network in regards to network design goals, which may differ from the goals of the individual user.

When attempting to predict the flows that would happen in the real world, we need to consider the behaviour of the users who are travelling through the network. In particular we need to consider what criteria the users use to evaluate different routes to achieve their goal of arriving at their destination.

3.1 Generalized Cost

The travel time on a particular link is one of many factors that influence the route choice of a user. While the travel time is the typically the dominating factor the combination of other factors can be significant enough to produce inaccuracies in results if not considered. Examples of such factors include distance, road type, safety, and road tolls.

To incorporate the factors present in users' route choice we introduce the concept of a generalized cost for each link. This generalized cost is formed by weighting and aggregating the various factors determined to be important in the users' perception of the cost of the link, and may be a function of other variables such as the traffic flow or traffic type.

3.2 User Behaviour

The next consideration is, given the perceived cost of each link, what decisions would a user make in regards to route choice. When attempting to model real life situations we generally model the users as selfish, taking the shortest route available to them, with the assumption that the user knows the travel time of each road at that instant, either through experience or knowledge of typical road conditions.

3.3 Equilibrium

Given that each user takes the shortest path available to them, we observe that there will always be a motivation for users to switch from the path they were assigned to as long as a lower cost path is available, and thus in a stable solution it must be the case that for all users the cost of alternative routes is greater or equal to their currently assigned route.

3.4 System Optimality

So far we have only considered 'user equilibrium', that is the equilibrium resulting from users choosing the shortest path available to them. However, there exists another equilibrium commonly used, termed the 'system equilibrium'. This equilibrium represents the state of minimum total travel time, where no collection of users can switch routes to reduce the total travel time.

This equilibrium state is of interest to network planners as they wish for the traffic flows to be close to this minimal travel time state. The differences between the system equilibrium flows and the real world or user equilibrium flows can help planners identify areas of the network which need improvement or modification to motivate users to switch to more system-optimal routes.

The way this system equilibrium is formulated is similar to that of the user equilibrium, with the primary change being that link costs are modified to reflect not only the cost incurred by the next user on the link, but to also include the extra cost incurred by the existing users on the link due to the increased congestion caused by the additional user.

$$c_a^{SE} = c_a(v_a) + v_a * \frac{\delta c_a}{\delta v}$$

The above equation shows how the cost c_a for an arc a is modified in a system equilibrium formulation when under a traffic volume of v_a, with the additional derivative term representing the increased congestion for exiting users.

4 Model Creation

This section details the steps that were required to build the model of Auckland's transport infrastructure, and to produce the demands on the network during the long weekend period. This process involved three main areas: the network, the demands, and the solver.

4.1 Network

The first step of the forming the model was to create or obtain the network representing Auckland's roads. The network we used in the project was based on the regional transport models developed and maintained by the Auckland regional council.

The current model in use by the Auckland regional council is the Auckland regional transport model 3 (ART3), shown in Figure 2. Consisting of 7,665 nodes and 14,752 links and including the Auckland region from Wellsford south to Papakura (ART3 Documentation, 2010). The ART3 model is the most detailed model available, in addition to containing the most accurate road cost functions, and as a result is the primary source for network data.

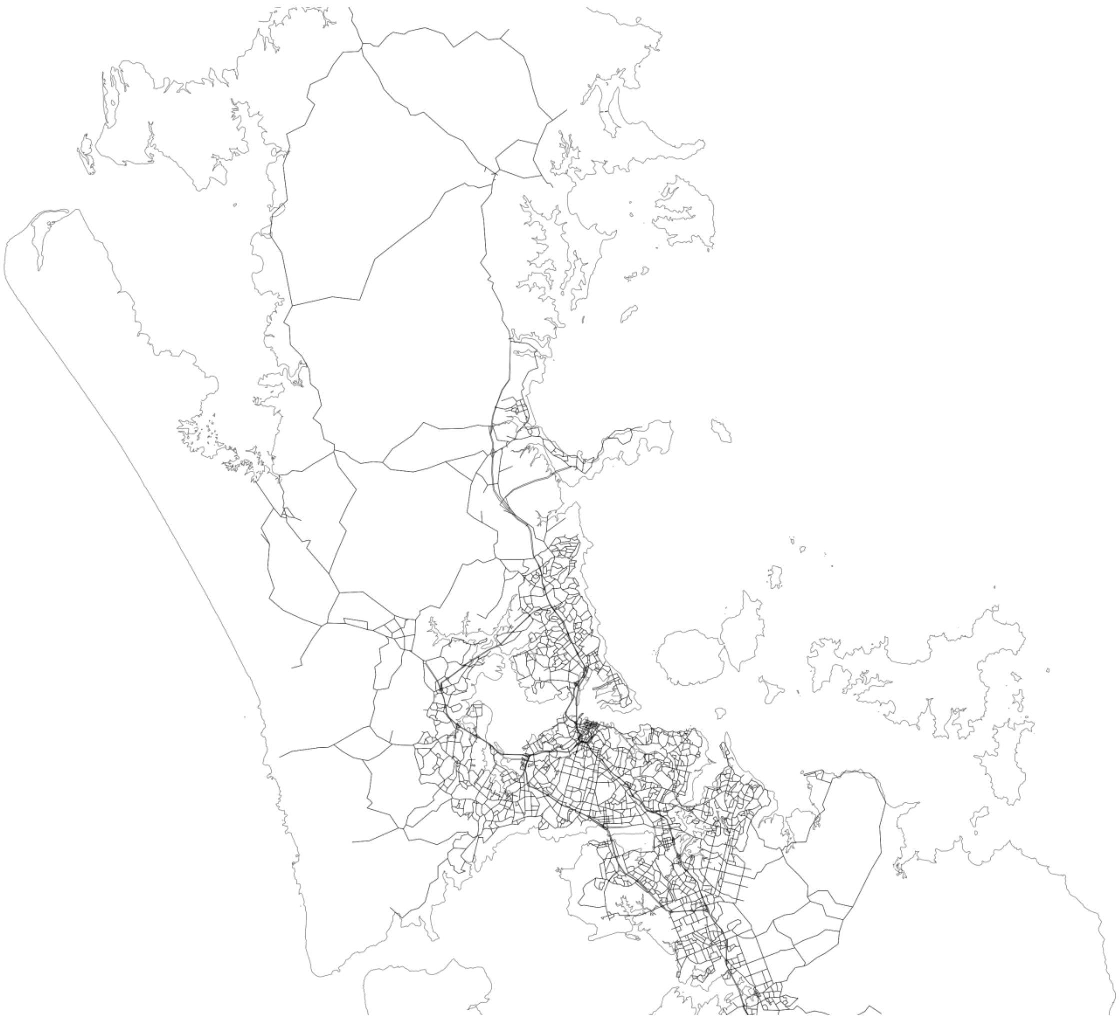

Figure 2. ART3 network

4.1.1 Computational Issues

When attempting to solve the full ART3 model with our solver we encountered numerous computational issues. The primary issue was that the large number of nodes and arcs present in the ART3 model were preventing the model being solved due to memory limitations.

Due to these computational issues, compromises had to be made with regards to the model size. To accomplish this we combined the ART3 with its predecessor, the ART2 model, shown in Figure 2. The ART2 model is much less detailed than the ART3 model, containing just 2353 nodes and 5753 links. This allowed us to considerably reduce the number of nodes in the network, while maintaining the accuracy of the network representation.

4.2 Demand

The next stage was to assess the demand on the model. The first consideration to be made was the period for which the demand is to be obtained. The focus of this project is how the network handles the demand spikes of events and public holidays, so the first stage involved analyzing hourly-count data provided by Sinclair Knight Mertz Ltd. This hourly-count data was collected from electric coils placed under the surface of the road which provides accurate data about the number of vehicles passing a particular point.

From the hourly count data for the year 2008, it was possible to identify the days of peak demand, and for each day the magnitude and pattern of that demand. From this the Auckland anniversary long weekend starting on the 26th of January was found to result in demand representative of the spike-demand produced at the beginning of most holiday periods.

For the project the inter-peak demand figures, representing the period from 9 am to 3 pm, were chosen to most accurately represent the state of Auckland's central roads during a public holiday periods, given that the inter-peak demand is evenly spread across the network, without large demand into or out of the CBD which has the potential to skew results.

5 Solver

The next stage of the modelling process, after obtaining the base network and the demands required, is the solving process. This involves the selection and implementation of a route choice algorithm to determine the resulting flows of a scenario. The solver used in the project was one written by Dr Andrea Raith, of the University of Auckland, this solver is based on utilizing repeated iterations to converge the solution towards the equilibrium state. It does this by examining each origin-destination pair and the routes which the corresponding demand is assigned to.

By identifying the shortest and longest route that the demand uses, flow may be transferred from the longest route onto the shortest route until the costs for each route become equal. This approach makes use of the observation that at equilibrium the costs of the routes used are equal, thus by identifying routes whose times are not equal and modifying our solution such that the costs become the same we iteratively drive the solution towards the equilibrium state.

This approach was first proposed by Dafermos & Sparrow (1969), and its convergence is proved in the same article, based on the principle that each time we equilibrate two paths we decrease the overall objective function value.

6 Validation

With the network constructed, demand figures obtained, and a method with which to solve for resulting flows, the next step was to validate the entire model. This was done by solving for user equilibrium, the state that is most likely to represent real life user behaviour and flows. This data was then compared to observed flow count data.

Results from the model indicated a flow of 1280 cars/hour going north on SH1, with 370 cars/hour using SH16. This was found to be consistent with the observed flow counts at data sites on state highways 1 and 16, with counts of 1250 cars/hour and 400 cars/hour respectively. In addition to validating against the main routes of SH1 and SH16, count data was also matched to model figures at sites between Warkworth and Wellford, and on SH1 from Wellsford north to Whangarei, the model was found to closely match collected data at these sites as well.

As an additional validation step the travel times to Wellsford and Warkworth from Auckland as calculated by the model were compared against figures published by the New Zealand Transport Agency (NZTA Website, 2010). The times reported by the NZTA for users on public holidays using the state highways were found to be consistent with the times reported by the model.

7 Results

To investigate the claim that SH16 is underused the baseline counts were compared to a modelled situation in which users are modelled as cooperating to achieve the minimum overall travel time, with particular users taking routes slower than their personal optimal route in order to benefit others drivers greater than their individual loss. This minimization of overall travel time is the optimal goal of transportation planners, so by comparing this result to the baseline result and observing the differences we can make conclusions on the performance of the network from a planning point of view, and identify areas that warrant attention or improvement.

When solving with users seeking to minimize total travel time, it was found that the usage of SH16 increased by 235 cars/hour to 605 cars/hour, with the usage of SH1 decreasing by a similar amount to 1025 cars/hour. This result confirms the opinion of NZTA that SH16 is underused, and that users switching from the primary route of SH1 to the alternative of SH16 would result in a lower total travel time for users travelling north on a public holiday.

With the model having confirmed that there is a net benefit for drivers if more drivers were to switch to SH16, we began investigating the situation of SH16 attempting to determine the main factors that are causing its underuse.

The first factor considered was that SH16 was disadvantaged by being far west, requiring drivers originating from central to eastern Auckland to travel cross-city before travelling north via SH16. Given that the majority of the demand originates at non-west locations, it is possible that the additional travel time from travelling cross-city makes SH16 unfavourable relative to the centrally located SH1 alternative.

To investigate this theory we modified the model, doubling the lanes of SH16 in the inner region of Auckland, this doubling of lanes doubles the practical capacity of SH16 which reduces the level of congestion and results in faster travel times. These changes to SH16 match changes currently proposed by NZTA in a project aiming to upgrade SH16 between St Lukes and Westgate, where the proposed changes include a doubling of the number of lanes, so by solving for this situation we also gain insight into how the network will perform if the proposed changes are undertaken in the future.

After solving for the user equilibrium we found that the usage of SH16 as a route north remained largely unchanged, in addition the usage of SH1 was also unchanged. This result indicates that the cross-city travel time is not a primary factor in users' decisions between taking SH1 or SH16 north. This lead us into the next potential factor, that the reason people do not choose SH16 is due to the performance of SH16 itself. In particular the fact that portions of SH16 consist of a single lane, which causes issues with passing and hence congestion can occur when slow moving vehicles such as trucks are present.

To evaluate whether the performance of SH16 itself is the cause for its underuse we solved the model after doubling the number of lanes on the entirety of SH16, from central Auckland north to Wellsford. Solving for this scenario showed a small increase of 30 cars/hour on SH16 for the user equilibrium model, and a larger increase of 40 cars/hour for the system equilibrium. While these results show an increase in usage of SH16 when extra lanes are added, they magnitudes of the increases indicate that the performance and hence usage of SH16 is not tied to its performance under congestion, but rather the larger distance that SH16 covers over the much shorter SH1, 80 km and 60 km respectively, especially for demand destined for Warkworth.

To determine whether the bottleneck in SH16s performance is due to the distance alone, over any congestion factors, the model was adjusted to give the highway 50 lanes in each direction, completely eliminating congestion effects from the model. When the model was rerun with these parameters and compared to the original model representing the current state of SH16, an increase of only 50 cars/hour on SH16 was observed.

Figure 3. Results

	User Equilibrium		System Equilibrium	
Scenario	SH1	SH16	SH1	SH16
Base counts	1250.0	400.0	-	-
Normal model	1225.3	369.3	994.7	601.3
2-lane SH16 inner-city only	1208.7	352.7	981.3	614.7
2-lane SH16	1192.0	403.3	956.7	637.3
50-lane SH16	1177.3	417.3	950.7	643.3

8 Conclusions

The results gathered from the model indicate that road users travelling north behave with the goal of minimizing their personal travel time, as expected, and that while SH16 is relatively uncongested on public holidays users still prefer to use the heavily congested SH1.

The reason for users choosing the congested SH1 over SH16 is due to SH1 being much shorter than the alternative SH16, which requires drivers to also travel cross-city and in the case of those travelling to Warkworth on SH16 requires them to use SH1 from Wellsford to Warkworth if they wish to stay on highway routes.

The users who do choose to use SH16 were found to be primarily from the far west region of Auckland, illustrated in Figure 15 and Figure 16, where the cross-city travel time penalty is moved from SH16 to SH1. The importance of this is that the users SH16 appeals to consist only of those living very close by, and that the extra distance incurred by those living away from SH16 combined with the already long length of the highway renders attracting additional users through improving SH16 infeasible.

Looking forward into future improvements to the road network north of Auckland, with the goal of reducing congestion on SH1, the primary candidates are either upgrading SH1 itself to raise its capacity and hence reduce congestion, or to introduce a new highway north of Auckland that either runs parallel to SH1, or is based in the west with the goal of cutting off long sections of SH16 with a more straight alternative.

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