APPLYING BI-OBJECTIVE SHORTEST PATH METHODS TO MODEL CYCLE ROUTE-CHOICE

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ABSTRACT

It is widely acknowledged that cyclists choose their route differently to drivers of private vehicles. Commuter drivers often have only one objective for their route-choice, to reduce their generalised travel cost, which is a combined monetary value representing the combined travel time and vehicle operating cost. Commuter cyclists, on the other hand, usually have multiple objectives when choosing their route: the travel time and the suitability of a route for cycling. Some of the factors that characterise the ‘suitability’, or ‘attractiveness’ of a route include the safety (i.e. traffic volumes, traffic speeds, presence of bicycle lanes) and whether the terrain is flat or hilly.

This paper summarises a study on the route-choice behaviour of commuter cyclists using bi-objective shortest path (BSP) methods. The two objectives considered are travel time and the attractiveness of a route. A method is developed to quantify the attractiveness of a route for cyclists and to identify fast and attractive routes. Rather than determining a single route for a cyclist, we determine a choice set of optimal alternative routes (efficient routes) from which a cyclist selects one according to their personal preference (according to their valuation of travel time versus other path criteria summarised as attractiveness).

This method is then implemented in a case study in Auckland. This study provides a starting point for the traffic assignment of cyclists, and with further research, the bi-objective shortest path model developed can be applied to create a complete travel demand model for cycle trips.

Keywords: Bi-objective shortest path methods, cycle route-choice, traffic assignment

1 INTRODUCTION

In transport planning, cycle trips are conventionally combined with walking trips under the term 'active modes'. Active modes are widely acknowledged to be efficient options for commuting trips, as they have no vehicle emissions, do not contribute to traffic queues, pose little risk to other road users and increase the health of the population. In fact, physical activity is considered to be one of the 'best value' methods of improving public health (Morris, 1994). Despite the benefits, exercise, such as cycling, tends to be promoted to the public as a leisure activity, rather than as a transport alternative (Ogilvie et al., 2004). One reason for this is that cycling can be perceived as a dangerous undertaking, especially in Auckland. High traffic volumes, narrow roads and a lack of cycle paths are just a few of the obstacles that cyclists must face. One British study (Lingwood, 2004) concludes that cycling cannot be promoted as a transport alternative, until the journeys can be undertaken in a safe, cycle-friendly environment. In order to achieve Auckland City Council’s vision of increasing the

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proportion of cycle trips (Auckland City Council, 1998), the most popular routes of cyclists need to be identified.

Thus, in order to increase cycle trips, a cyclist's safety must be improved. Providing cycle-specific infrastructure, such as a bicycle lane or path, is the most obvious means of achieving this (Dill and Carr, 2003). However, with limited funding available for these facilities, their placement within a road network is very important. In order to do so, we will need to be able to pinpoint sections of the road network with the highest cyclist volumes. From here, these areas can be targeted to become more cycling-friendly, and cycling to work can then be more effectively promoted as a feasible alternative to commuting by car.

In a conventional four-stage transport planning model, route-choice is modelled in the final stage, traffic assignment. Traffic assignment is performed for private vehicle and public transport trips in order to determine the link volumes in terms of vehicular flow and patronage on public transport services. Cycle trips are not modelled at all in this stage. In practice, walk and cycle trips are often represented as one ‘active mode’ trip matrix determined in the third stage, modal split, which will be put aside only for reference. As traffic assignment is often not performed for cycle trips (e.g. in Auckland), it will not be possible to perform an economic evaluation for cycle network improvement in the conventional way as what is normally carried out for road improvement projects.

As a starting point, we will need to model cyclists’ route-choice behaviour. This route-choice model can then become the building block for the development of a cyclist traffic assignment model, from which we will be able to determine the link volumes on a cycle network. The purpose of this study is to develop a route-choice model for cyclists with a bi-objective shortest path method.

The model developed is applied to a case study in New Zealand. We analyse Auckland's commuting trips in the morning peak period, between a representative origin and destination in the Auckland City region.

2 LITERATURE REVIEW

Before a road network can be analysed for its suitability for cyclists, a detailed understanding of the needs of cyclists is required. The purpose of this literature review is to analyse the factors that affect cycle route-choice, find an empirical method to quantify the qualitative factors, and consider methods that analyse these factors at the same time, so that the best routes for cyclists can be found.

2.1 Route-Choice Behaviour of Cyclists

In order to understand the route-choice behaviour of commuter cyclists, the factors that influence their choices must be understood. Numerous studies outline and model these factors, and it is unanimously identified that travel time is the most important influence for the route-choice decision (Dill and Carr, 2003, Stinson and Bhat, 2003, Aultman-Hall et al., 1997). Thus, when analysing the route-choice factors, travel time can be separated from all the other ones.

However, there are numerous other factors that affect route-choice. Some of these factors are subjective (such as cost, physical fitness and valuation of time) and cannot be quantitatively assessed (FHWA U.S. Department of Transportation, 1992). Other factors such as motor traffic volume, presence of cycle facilities and topography are objective, so can be evaluated in a route-choice study. In this study, these objective factors are aggregated into the term ‘attractiveness’; a generic term that describes how suitable (i.e. safe and comfortable) a road is for cyclists without presuming a valuation that of course depends on each individual cyclist.

2.2 Methods to Quantify Route-Choice Factors

For attractiveness to be considered as one of the factors, it is crucial to find a systematic way of evaluating how suitable a route is for cyclists. A Land Transport Safety Authority (2004) report suggests performing a Bicycle Level of Service (BLOS) assessment to evaluate how suitable a route is for cyclists.

Three main BLOS methods have been identified in the literature. Two studies in the United States (Harkey et al., 1998), (Florida Department of Transportation, 2002) came up with technically sound BLOS methods, but they do not consider some factors that are important to Auckland's cyclists, such as road gradient. A study in the United Kingdom (Institute of Highways and Transportation, 1998) developed a comprehensive assessment method that evaluates a route's attractiveness against more factors than the other two methods. It is designed to minimise subjective factors, and to consider cycle trips in their entirety, rather than focussing only on each individual link.

2.3 Considering Two Objectives Simultaneously

For modelling purposes, the factors influencing cyclist route-choice can be simplified into two categories:

- Route-level, such as travel time; and
- Link-level, such as attractiveness, safety and comfort.

Conventional traffic assignment methodologies are based on the assumption that all drivers have one single objective. However, a problem arises when modelling cyclists, as their decision is based on more than one objective. Therefore, a bi-objective route-choice model, based on the two categories outlined above, is more appropriate to model cyclists' route-choice decisions. BSP techniques can analyse two independent factors at the same time (Raith and Ehrgott, 2009).

3 NETWORK CODING

Before cycle route-choice can be modelled in terms of the two objectives, the travel time and the 'attractiveness' of a route, Auckland's road network in the traffic assignment model has to be modified. This section discusses how a cycle network is coded for the study area.

The study area for this research is defined as a representative trip between two zones in the Auckland region (the shaded regions A and B in Figure 1 below), with all the possible routes between the given origin and destination being assessed.

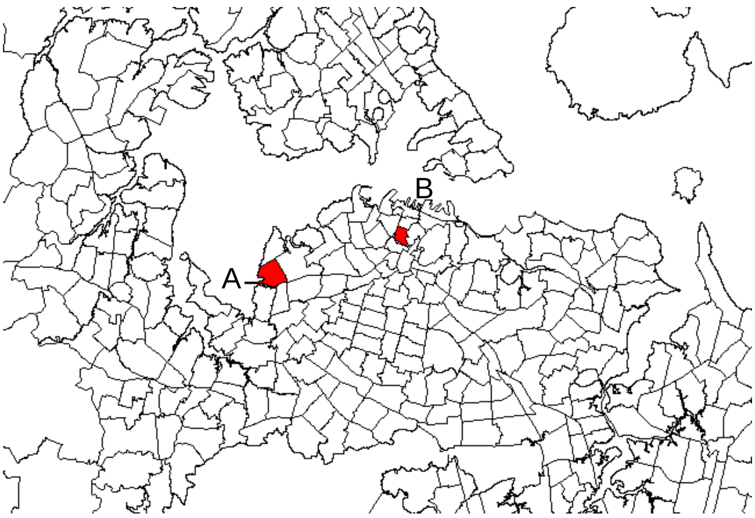


Figure 1: Zone Plan of Auckland Region in the Auckland Regional Transport Planning Model (Source: Auckland Regional Council)

Zone A represents a residential zone in Point Chevalier, and zone B corresponds to a commercial zone in Auckland's Central Business District. A trip from zone A to B represents a typical trip for a cyclist's morning commute in Auckland.

The cycle network is obtained by modifying the road network modelled in the Auckland Regional Transport (ART) Planning Model, provided by Auckland Regional Council (ARC). The ART model road network consists of nodes, which correspond to large intersections, and links, that represent mid-block sections of road. Additional links are put into the network, in locations where only bikes are permitted, such as an off-road cycle path.

However, as outlined in Section 2.1, cyclists tend to have more objectives than drivers; they base their route-choice not just on travel time, but numerous other factors that can be combined into the term 'attractiveness'. Next, we introduce the two factors, time and attractiveness, that determine the route-choice of cyclists.

3.1 Travel Time Objective

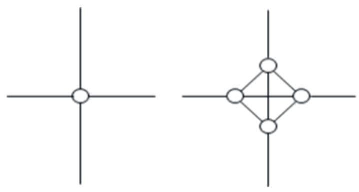
3.1.1 Link Travel Time

For vehicle traffic, the travel time on each link is approximated by a volume-delay function, e.g. typically a BPR function (Bureau of Public Roads, 1964) can be applied to determine the average travel time to traverse a link as a function of the traffic volume on this link. However, this is not applicable to cyclists, as they do not tend to wait in traffic queues, instead passing the queue on the inside. Therefore, a new travel time function, which is based purely on distance, is assigned to the links of the road network. The link distances are derived from the Geographic Information Systems (GIS) coordinates of the nodes and links in the ART model road network. The new function assumes a fixed velocity for cyclists across the whole network.

In reality, gradient also affects the speed of cyclists, and therefore their travel time. However, our model does not include gradient in the travel time factor. The hills in Auckland are relatively short in length, thus have a negligible effect on cycle speed. Gradient is still a major route-choice factor for cyclists, so we include it as part of the second objective of the model, as an 'unattractiveness' factor. This will be discussed in Section 3.2.1.

3.1.2 Intersection Delay Time

For a commuting trip, travel time not only includes mid-block sections of road; delay at signalised intersections also makes up a considerable portion of the trip. In the ART model road network, intersections are typically represented by a single node with no additional delay, as shown in Figure 2(a). To account for the increased travel time, the intersections in the road network need to be modified.



(a) (b)

Figure 2: Modification of intersection node layouts.

Nodes in the road network that correspond to large, signalised intersections are modified with 'dummy' nodes and links, as demonstrated in Figure 2(b). The travel times on these dummy links represent directional delays at the intersection.

A realistic delay value needs to be calculated for the new dummy links. An average delay is estimated for the signalised intersections.

Assuming that cyclists do not have to queue at traffic signals (i.e. because of their small size, they can manoeuvre through queues and get to the front relatively easily), a 'cyclist stop rate' for each approach can be approximated as the proportion of the signal cycle that is red (red time / signal cycle time). Furthermore, the average delay for stopped cyclists can be represented as half the red time (red time / 2). Multiplying the cyclist stop rate by the average delay for stopped cyclists, gives the average delay for all the cyclists on each approach:

$$\text{average delay} = \frac{R_t^2}{2C_t} \quad \text{Average delay} = \frac{R_t^{\,2}}{2C_t} \qquad (1)$$

where R_t is the red time for a given approach and C_t the total signal cycle time.

This formula is based purely on average phase times, and accounts for the fact that cyclists arriving in the green period will not have any additional delay.

Actual traffic signal phasing data is obtained from the Auckland City Council's Sydney Co-ordinated Adaptive Traffic System (SCATS). For this study, all of the 15 signalised intersections in the study area are coded to include directional links, then individually assessed to calculate the directional delays associated with each link.

3.2 Attractiveness Objective

The numerous other factors (grouped into the term 'attractiveness') that affect route-choice need to be considered in the second objective associated with each link of the cycle network.

3.2.1 Attractiveness Rating for each Link

A systematic method is required to quantify how attractive, or safe, a certain section of road is for cyclists. As discussed earlier, there are several BLOS methods in the literature that can be applied to quantify this attractiveness value. We consider the British method mentioned in Section 2.2 of 'Guidelines for Cycle Audit and Cycle Review' (Institution of Highways and Transportation, 1998), which provides a more extensive analysis than the others, to be the most applicable method for Auckland City's traffic conditions. This procedure allows 'attractiveness', a qualitative measure, to be converted into a quantitative value.

In total, 20 road factors are accounted for in the 'Cycle Review' attractiveness rating system. Some of these are:

- Motor traffic volume;
- Motor traffic speed;
- Road lane width;
- Presence of on-street parking;
- Gradient of road;
- Percentage of heavy commercial vehicles;
- Provided cycle facilities, such as cycle lanes or shared bus/cycle lanes; and
- Pavement condition.

The 'Cycle Review' method uses a scoring system to convert the above factors to a simple A-F score. Road characteristics data are collected for all of the links in the study area, then put into the 'Cycle Review' model. The output of this step is a score out of 100 for each link, which corresponds to a grade from A-F, as shown in Table 1.

The grades A-F are converted into to a 1-6 integer value in the last column of Table 1,

Table 1: Scoring system for the attractiveness method.

Attractiveness Rating	Score	Integer value
A	81-100	6
B	61-80	5
C	41-60	4
D	21-40	3
E	1-20	2
F	≤0	1

as a quantitative measure of attractiveness. Therefore, each link in the study area can be assigned an attractiveness value as a second attribute, which quantifies the suitability of the link to cyclists.

Crash data is not included as a representation of cycle safety. Previous cycle crash history can indicate unsafe parts of the road network, however, there are numerous limitations in the data: there are many contributing factors to a crash that cannot be modelled; and bicycle crashes are often unreported (Land Transport Safety Authority, 2004). Thus, using crash analysis data cannot be relied upon when modelling cycle safety. This study assumes that crashes only occur due to road geometry and traffic properties.

3.2.2 Intersection Attractiveness Rating

As intersections have been modelled to account for additional travel times, it is also required to calculate an attractiveness value for these intersections. There is very little documented research that rates intersections for their attractiveness to cyclists. The only existing method is from the United States, which rates the safety of intersections for the bicycle through movement (Landis et al., 2003). To arrive at an attractiveness rating, this method considers lane widths, crossing distances, traffic volume; and the number of through lanes for a given approach.

Each SCATS-controlled signalised intersection in the study area is analysed for these factors, and by applying the method recommended by Landis et al. (2003), an A-F attractiveness rating is determined for the through movements at all of these intersections. This method, however, is not applicable to turning movements. In this study, we determine the attractiveness rating for turning movements based on the number of through lanes and the gradient of the approach to the intersection.

3.2.3 Measuring the Attractiveness of a Path

Unlike travel time, the attractiveness of a path cannot be represented by the sum of the attractiveness ratings of each link. Therefore, a method to convert the attractiveness values of the links into a cumulative figure has been developed. The attractiveness rating $a(p)$ $\bar{a}(p)$ along path p is given by:

$$a(p) = \frac{\sum_{i \in p} t_i a_i}{t(p)} \qquad \overline{a(p)} = \frac{\sum_{i \epsilon p}(t_i a_i)}{t(p)} \qquad (2)$$

(2)

where $a(p)$ $\bar{a}(p)$ is the attractiveness score for the entire path p, a_i the attractiveness score for the ith link, $t(p) = \sum_{i \in p} t_i$ the total travel time for p, and $\sum_{i \epsilon p} t_i$ t_i the travel time on the ith link.$\sum_{i \epsilon p} t_i$

4 Analysis of Modified Network

As discussed earlier, the conventional approach in traffic assignment assumes that all drivers have one single objective, i.e. to minimise generalised travel cost. A cyclist, on the other hand, wants to minimise their travel time as well as choose a route of maximal attractiveness. The most attractive route may well be slower than the fastest route. Thus, BSP techniques are required to model the route-choice of cyclists.

4.1 Bi-objective Shortest Path

In BSP, instead of obtaining "the" best solution, the aim is to generate a set of good compromise solutions. We call those routes (or paths) efficient. Efficient routes are those, whose attractiveness level would not improve when trying to improve its travel time by switching to another route and vice versa. An equivalent definition calls a route efficient if there is no other route that is better in one of the objectives, e.g. time, and at the same time not worse in the other objective, e.g. attractiveness. Figure 3 shows the travel time and attractiveness of different paths. In the figure, the travel time and attractiveness of efficient paths is marked by a dot, whereas time and attractiveness of all other paths are indicated by 'x'. For every path marked by an 'x', there exists at least one efficient path, indicated by a dot, with better value in both time and attractiveness.

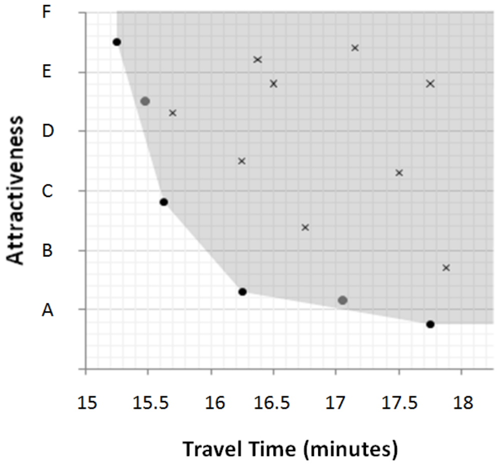


Figure 3: BSP example output: efficient paths

We formalise these concepts in the following. Let $p=(i_1,i_2,\dots,i_n)$ $\mathrm{p} = (\mathrm{i}_1, \mathrm{i}_2, \dots, \mathrm{i}_n)$ be a path (or route) consisting of the links with indices $i_1,i_2,\dots,i_n$ $\mathrm{i}_1, \mathrm{i}_2, \dots, \mathrm{i}_n$. By P we denote the set of all paths. The path p p has travel time $t(p)$ and attractiveness level $a(p)$ $\overline{\mathrm{a(p)}} = \frac{\sum_{i\in p}(t_i a_i)}{t(p)}$. Formally, path $p \in P$ is efficient if there exists no path $p' \in P$ such that

$$t(p') < t(p) \text{ and } a(p') \ge a(p)$$

or $$t(p') \le t(p) \text{ and } a(p') > a(p) \tag{3}$$

If, on the other hand, there *does* exists such a path p', we say that p' dominates p.

In order to obtain all efficient paths, the suitable path choices for cyclists, a bi-objective shortest path algorithm is used. This BSP algorithm is applied to find all efficient paths between the given origin and destination. This modeling technique enables us to consider the two route-choice factors simultaneously.

4.2 Solving the Cyclist BSP problem

A bi-objective label correcting algorithm is used to solve the BSP problem, for details see (Raith and Ehrgott, 2009). Unfortunately, the problem with the original objectives

$$\min\left\{\sum_{i\in p} t_i : p \in P\right\} \qquad \text{and} \qquad \max\left\{\frac{1}{t(p)}\left(\sum_{i\in p} t_i a_i\right) : p \in P\right\} \tag{4}$$

cannot be solved by this algorithm as a basic assumption that guarantees convergence of the algorithm is not satisfied. This assumption is that the two separate objectives increase in value when an additional link is added to a path.

We can, however, show that efficient solutions of (4) are always efficient solutions of the auxiliary problem (5) obtained by dropping the denominator of $a(p)$ in (4).

$$\min\left\{\sum_{i\in p} t_i : p \in P\right\} \qquad \text{and} \qquad \max\left\{\sum_{i\in p} t_i a_i : p \in P\right\}. \tag{5}$$

Problem (5) satisfies the assumption that the objective function values of a path increase as an arc is added to it. Hence the bi-objective label correcting algorithm can be used to find all efficient paths without cycle, i.e. those paths in which no link appears twice. Once all efficient solutions of (5) are obtained, those among them that are also efficient for (4) are selected, and the problem is solved.

It remains to prove that an efficient path of (4) is always an efficient path of (5). In order to do so, assume the contrary, i.e. there exists an efficient path p of (4) that is not efficient for (5). Therefore, there exists a path p', that dominates p for (5). Then, by (3)

$$\sum_{i \in p'} t_i < \sum_{i \in p} t_i \text{ and } \sum_{i \in p'} t_i a_i \geq \sum_{i \in p} t_i a_i$$

or

$$\sum_{i \in p'} t_i \leq \sum_{i \in p} t_i \text{ and } \sum_{i \in p'} t_i a_i > \sum_{i \in p} t_i a_i ,$$

which implies that

$$\frac{\sum_{i \in p'} t_i a_i}{\sum_{i \in p'} t_i} > \frac{\sum_{i \in p} t_i a_i}{\sum_{i \in p} t_i}$$

Therefore, p' dominates p for (4), a contradiction to p being an efficient solution of (4).

5 RESULTS

Figure 4: Results of the study – the efficient paths (Source of Aerial Map: Auckland City Council).

All existing links have been modified to include the two link attributes for cyclists. New nodes and links have been created where required, such as along an off-road cycleway and at intersections. Upon solving the BSP problem, the efficient paths are obtained. Figure 4 shows the efficient paths superimposed on an aerial map of the study area. It should be noted that while the striped path is the shortest one, most paths use at least

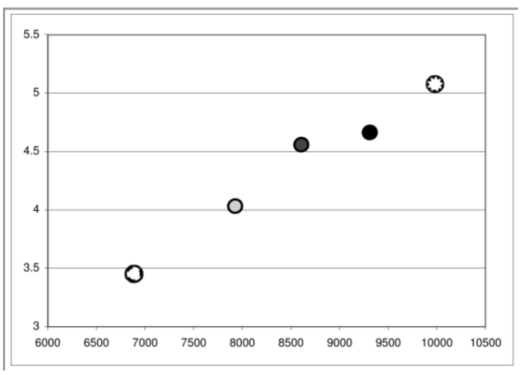


Figure 5: Time and attractiveness of efficient paths.

part of the longer off-road cycleway parallel to the motorway (e.g. the black and dotted paths).

The BSP output corresponding to the efficient paths is shown in Figure 5. Each of the points on the graph represents the total travel time and attractiveness rating for an efficient path.

6 DIRECTIONS FOR FUTURE RESEARCH

6.1 Calibration and Validation

Calibration of the model must be performed, in order to reflect the sensitivity of the travellers. The 'Cycle Review' method (Institute of Highways and Transportation, 1998), which has been used to quantify the attractiveness of a section of road, is a regression model where the coefficients are standardised for British cyclists. However, although the factors included in the model are present for every cyclist, each cyclist would weigh these factors differently. Where two cities have differences in terrain and traffic conditions, the coefficients in the regression model will always change.

In order to calibrate the model for Auckland City, a full calibration study is required. This would involve setting up 'test routes' around Auckland City, sending a large sample of cyclists along these routes, and getting them to rate the attractiveness of each section of the route. Statistical analyses could then be performed to correlate the attractiveness ratings with the road properties. This would allow the coefficients in the 'Cycle Review' model to be altered to reflect characteristics of Auckland's cyclists.

For validation, data are obtained from a 2007 Auckland Regional Council Cycle Survey, where the routes of cyclists around Auckland have been monitored over a period of two weeks. The survey's most popular routes in the study area are compared to the output from our network model. Unfortunately, despite some encouraging initial comparisons, the sample size of the ARC survey is far too small to obtain any meaningful correlations. Therefore, further validation of the results of this study is required with a detailed survey of commuter cyclists with bigger scale and larger sample size.

6.2 Creation of a Cycle Map

In order to promote cycling as a viable alternative to commuting by car, a cycle map could be created to recommend the 'best' routes for a cyclist between the two zones; a route that is the best compromise of travel time and attractiveness for an average commuter cyclist. One possible way is to apply an arbitrary constraint, such as *'the best path is the path with the fastest travel time, such that the average attractiveness rating is better than a C'.* A cycle map can be created by applying this method to all origin-destination pairs, which could be distributed to the public in an effort to promote cycling as an alternative mode of transport.

6.3 Travel Demand Modelling

To support transport planning decisions, such as evaluating infrastructure investment options for improvement of cycling facilities, estimating the expected usage of facilities would be required. In order to do so, we will need to develop a traffic assignment model for cycle trips. By applying the BSP method, we will be able to find the efficient paths for cyclists for each origin-destination pair. This becomes the choice set for the cyclist. Individual preference will depend on the cyclist. For example, an experienced commuter cyclist might not worry about the hilliness or safety of the route, and choose the route with the lowest travel time. On the other hand, a different type of cyclist may value safety much higher than an experienced cyclist, therefore choose the most attractive, but longest route. Thus, further research is required to develop an assignment method to assign the cyclists to their preferred route. Conventional traffic assignment methods, e.g. deterministic traffic assignment model based on Wardrop's principle (Wardrop, 1952), will not be directly applicable to cycle trips since Wardrop's principle is based on a single objective assignment.

7 CONCLUSIONS

Cyclists' route-choice is currently not modelled in a conventional four-stage transport planning model. It is well known that cyclists behave differently from drivers of motor vehicles as they consider multiple objectives in their decisions. The conventional way of considering generalised cost as the single objective does not apply to cyclists. We have made a first attempt to model commuter cyclists' route-choice with a bi-objective shortest path method, by classifying factors influencing their decision into two categories, namely, travel time and attractiveness. Given an origin-destination pair, the model can be applied to identify the route-choice set, i.e. the set of efficient paths, based on the criteria considered. We apply the model developed to a case study in Auckland. However, the method of assessment for route attractiveness has to be calibrated and validated for Auckland before it can be applied on a network wide basis.

Areas for further research are identified. The model developed can be applied to create a cycle map for the region to promote the use of bicycles for commuting. Moreover, with further research in bi-objective assignment methodologies, the model can also become the building block of a traffic assignment model for cycle trips.

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9 REFERENCES

AUCKLAND CITY COUNCIL (1998) Cycling and Walking Strategy. Auckland City.

AULTMAN-HALL, L., HALL, F. & BAETZ, B. (1997) Analysis of Bicycle Commuter Routes Using Geographical Information Systems: Implications for Bicycle Planning. Transportation Research Record, 1578, 102-110.

BUREAU OF PUBLIC ROADS (1964) Traffic Assignment Manual. IN U.S. DEPARTMENT OF COMMERCE; URBAN PLANNING DIVISION (Ed.). Washington D.C.

DILL, J. & CARR, T. (2003) Bicycle Commuting and Facilities in Major U.S. Cities: If You Build Them, Commuters Will Use Them. Transportation Research Record, 1828, 116-123.

FHWA U.S. DEPARTMENT OF TRANSPORTATION (1992) Case Study No. 1: Reasons Why Bicycling and Walking Are Not Being Used More Extensively as Travel Modes.

FLORIDA DEPARTMENT OF TRANSPORTATION (2002) Quality / Level of Service Handbook. Tallahassee.

HARKEY, D., REINFURT, D. & KNUIMAN, M. (1998) Development of the Bicycle Compatibility Index: A Level of Service Concept. Transportation Research Record, 1636, 13-20.

INSTITUTION OF HIGHWAYS AND TRANSPORTATION (1998) Guidelines for Cycle Audit and Cycle Review.

LAND TRANSPORT SAFETY AUTHORITY (2004) Cycle Network and Route Planning Guide.

LANDIS, B., VATTIKUTI, V., OTTENBERG, R., PETRITSCH, T., GUTTENPLAN, M. & CRIDER, L. (2003) Intersection Level of Service for the Bicycle Through Movement. Transportation Research Record, 1828, 101-106.

LINGWOOD, P. (2004) Promoting walking and cycling as an alternative to using cars: Perception of safety is biggest obstacle BMJ, 329, 7476.

MORRIS, J. N. (1994) Exercise in the prevention of coronary heart disease: today's best buy in public health. Med Sci Sports Exercise, 26, 807 - 814.

OGILVIE, D., EGAN, M., HAMILTON, V. & PETTICREW, M. (2004) Promoting walking and cycling as an alternative to using cars: systematic review. BMJ, 329, 763.

RAITH, A. & EHRGOTT, M. (2009) A Comparison of Solution Strategies For Biobjective Shortest Path Problems. Computers and Operations Research, 1299-1331.

STINSON, M. A. & BHAT, C. R. (2003) Commuter Bicyclist Route Choice: Analysis Using a Stated Preference Survey. Transportation Research Record, 1828, 107-115.

WARDROP, J. G. (1952) Some Theoretical Aspects of Road Traffic Research. Proceedings of the Institution of Civil Engineers, Part II, 1, 325-362.