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A bi-objective cyclist route choice model

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ABSTRACT

It is widely acknowledged that cyclists choose their route differently to drivers of private vehicles. The route choice decision of commuter drivers is often modelled with one objective, to reduce their generalised travel cost, which is a monetary value representing the combined travel time and vehicle operating cost. Commuter cyclists, on the other hand, usually have multiple incommensurable objectives when choosing their route: the travel time and the suitability of a route. By suitability we mean non-subjective factors that characterise the suitability of a route for cycling, including safety, traffic volumes, traffic speeds, presence of bicycle lanes, whether the terrain is flat or hilly, etc. While these incommensurable objectives are difficult to be combined into a single objective, it is also important to take into account that each individual cyclist may prioritise differently between travel time and suitability when they choose a route.

This paper proposes a novel model to determine the route choice set of commuter cyclists by formulating a bi-objective routing problem. The two objectives considered are travel time and suitability of a route for cycling. Rather than determining a single route for a cyclist, we determine a choice set of optimal alternative routes (efficient routes) from which a cyclist may select one according to their personal preference depending on their perception of travel time versus other route choice criteria considered in the suitability index. This method is then implemented in a case study in Auckland, New Zealand.

The study provides a starting point for the trip assignment of cyclists, and with further research, the bi-objective routing model developed can be applied to create a complete travel demand forecast model for cycle trips. We also suggest the application of the developed methodology as an algorithm in an interactive route finder to suggest efficient route choices at different levels of suitability to cyclists and potential cyclists.

1. Introduction

Without a doubt cycling is one of the most energy efficient and healthy transport modes. Active modes, including walking and cycling, are widely acknowledged to be efficient options for commuting trips, as they cause no vehicle emissions, do not contribute to traffic queues, pose little risk to other road users and increase the health of the population. Although cycling in places of high air pollution might result in adverse health outcomes (de Nazelle et al., 2009), physical activity is considered to be one of the best value methods of improving public health (Morris, 1994; Lindsay et al., 2011). 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). For example, commuting cycle trips constitute only 1.9% of all the Journey-to-Work trips in New Zealand

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(Statistics New Zealand, 2008). One reason for this is that cycling can be perceived as a dangerous undertaking. High traffic volumes, narrow roads and a lack of cycle paths are just a few of the obstacles that cyclists must face. A study in the UK (Lingwood, 2004) concludes that cycling cannot be promoted as a transport alternative until the journeys can be undertaken in a safe, cycle-friendly environment. A lot of research effort has been devoted to finding ways to promote the use of active modes in transport, e.g. Pucher and Buehler (2008) in Europe, Gatersleben and Appleton (2007), Wardman et al. (2007) in the UK, and Akar and Clifton (2009), Dill and Carr (2003) in the US.

Like many other cities in the world, the City Council in Auckland, New Zealand, would like to promote positive attitudes towards cycling and walking and recognises the need to provide more and better facilities (Auckland City Council, 2007). In order to achieve Auckland City Council's vision of increasing the proportion of cycle trips, it is important to identify the locations where investment in cycling infrastructure would be most valued and hence the overall utilisation of the cycling network in the region can be improved. This involves understanding travel behaviour of cyclists and potential cyclists (those who currently choose not to cycle), and factors influencing cyclists' decisions on destinations, whether to bike or not, and on route choices. Ideally such information should be put together in a comprehensive travel demand forecast model for cycle trips, which can be applied in strategic analysis of different cycling facility improvement schemes.

The conventional four-stage transport planning model (de Dios Ortúzar and Willumsen, 2001) has been applied in travel demand forecast for decades. The model comprises of four stages, namely, trip generation, trip distribution, modal split and trip assignment. The first stage of *trip generation* involves determining the numbers of trips expected to leave each zone and the number of trips expected to arrive in each zone. The second stage, *trip distribution*, is the stage where the numbers of trips generated are distributed, that is, the number of trips between zones is calculated. A complete total trip matrix is obtained from this stage. The third stage, *modal split*, determines the number of trips by the different modes of transport available (e.g. by private vehicles, bus, rail, etc.). Finally, the fourth stage, *trip assignment*, is the procedure by which the planner predicts the paths the trips will take. As a result, the output of the four-stage transport model shows the paths that all trips will take, the number of cars on each roadway, and the number of passengers on each public transport route. Travel demand on roadways and public transportation systems is determined at the end of the fourth stage known as traffic assignment, which performs the route choice analysis for private vehicle and public transport trips. Link volumes in terms of vehicular flow and patronage on public transport services can be obtained in this stage. In practice, however, this stage often does not apply to cycling and walking trips. For example, in the Auckland Regional Transport (ART) model, as described in Davies et al. (2009), the total number of *active* mode trips (walking and cycling) originating from each zone are generated but trip matrices for pedestrians and cyclists are not produced and their route choices are not modelled at all.

Several cities offer online route planners providing cycling options. The Vancouver Cycle Trip Planner (http://cyclevancouver.ubc.ca) has options for cycling routes following the shortest path, the least traffic pollution, the least elevation gain, the most vegetated path and allows restrictions on slopes. It lets users choose between designated and alternate cycling roads only or the inclusion of major roads. The Los Angeles Route Planner (http://opt.berkeley.edu) similarly enables searches for cycling routes avoiding elevation gain, avoiding pollution, preferring green space, and avoiding prior bicycle accidents. Moreover it allows users to set preferences on a scale from 1 to 10 for six criteria. The San Francisco Bicycle Trip Planner (http://amarpai.com/bikemap/) can find a balanced route or the shortest or most bike-friendly route. It allows restrictions on gradient. The Sacramento Region Bicycle Trip Planner (http://www.sacergion511.org/bicycling/trips) has options for the shortest and most bike-friendly route. We observe that all of these online tools (naturally) allow a search for the shortest path route and in addition the search for a route according to one or more criteria that we may describe as measuring bicycle-friendliness or suitability for cycling. However, all route planners listed above find only a single route which is arguably the best according to some aggregated objective incorporating the available criteria. E.g., in the case of Los Angeles the user-defined preferences are used to aggregate the various criteria into a single objective used in the route search.

Despite the availability of cycling route planners, cyclist route choice is rarely modelled in the literature. In fact, this is a very challenging task. Route choices of commuting private vehicle drivers are conventionally modelled based on the assumption that they all behave in the same way and have only one objective, i.e. to minimise their travel time or the generalised cost (Wardrop, 1952). Generalised cost is an aggregation of two factors that are strongly correlated, travel time and vehicle operating costs. Unlike commuting drivers, cyclists often consider objectives that are not necessarily correlated with travel time. Other considerations, such as safety, cannot be ignored, because safety could be a factor as important as time, if not more important. It is easy to imagine the shortest route being unsafe because it follows a major road, whereas a longer route following a dedicated cycle path is perfectly safe.

Numerous studies in the literature confirm that safety considerations have a significant influence on cyclists' behaviour, e.g. Akar and Clifton (2009), Dill and Carr (2003), Hopkinson and Wardman (1996), etc. It is interesting to note that Hopkinson and Wardman (1996) found that safety is more highly valued than time in a stated preference survey conducted in Bradford, West Yorkshire, to estimate the value placed on different attributes on four alternative cycle routes. Furthermore, each individual cyclist may have a different perception of time versus safety. Hence we believe it is important not to combine these objectives into a generalised cost function even though this is standard practice when modelling private vehicle drivers in conventional route choice models.

The literature on modelling cyclists' route choices dates back to the 1980s. Bovy and Bradley (1985) were the first to apply discrete choice models in this area. A stated preference approach was applied to model commuting cyclists' route choice based on three route attributes, namely, time, traffic level, and surface quality. Until today, discrete choice models remain the mainstream technique in modelling the travel behaviour of cyclists. Hunt and Abraham (2007) performed a stated preference experiment in Edmonton, Canada, to examine various influencing factors on bicycle use. Route attributes are considered in more detail. For example, minutes riding on roadways in mixed traffic, on designated bike lanes, and on bike paths shared with pedestrians are considered separately. Other attributes such as experience of the cyclist, availability of secure parking and shower facilities at the destination are also considered.

It is not surprising that discrete choice models remain the mainstream approach in modelling cyclists' travel behaviour, because their decisions are multi-objective in nature and their preferences would depend on personal taste as well as their level of competence in cycling. This can be illustrated in the findings of numerous studies in the literature. Howard and Burns (2001) analysed the actual route choices of commuters of the Phoenix metropolitan area in a geographic information system. The actual routes are compared with three other sets of routes optimised based on different criteria: (1) distance; (2) time; and (3) safety. The comparative analysis produced mixed results. The shortest-distance routes resembled most closely the observed routes. This is consistent with findings from other studies, e.g. Stinson and Bhat (2003), Aultman-Hall et al. (1997). Antonakos (1994) also found that environmental factors such as traffic volume and surface quality do have an impact on cyclists' preferences. Shafizadeh and Niemeier (1997) suggest that separate bicycle paths play an integral part in the overall bicycle transportation network and more recently, Krizek et al. (2007) found that cyclists travelled, on average, 67% longer in order to include a cycle path facility on their route in Minneapolis, Minnesota. Tilahun et al. (2007) found that cyclists are willing to travel up to twenty minutes more to switch from an unmarked on-road facility with side parking to an off-road cycle path. There is no doubt that commuter cyclists did not choose routes solely based on safety, shortness or directness, but rather on some combination of these factors (Howard and Burns, 2001).

It is interesting to note that the common observation of the shortest-distance routes resembling most closely the observed routes in the revealed preference studies (Aultman-Hall et al., 1997; Howard and Burns, 2001) is somehow inconsistent with Hopkinson and Wardman (1996)'s finding of safety being more highly valued than time, although the observation in the latter case is related to investment preference rather than route choice. One possible explanation is that those who value safety higher than time are the ones who would choose not to cycle and therefore they would not have been in the samples of the route choice studies. This explanation is confirmed by a study of Winters et al. (2011), who aim to determine the major factors influencing the decision to cycle in Vancouver, Canada. The analysis of their survey reveals that the safety related factors "The route is away from traffic noise and air pollution" and "The route has bicycle paths separated from traffic for the entire distance" are among the top three motivators. On the other hand, "The route has surfaces that can be slick when wet or icy when cold", "The route is not well lit after dark" and "The risk of injury from car-bike collisions" are three of the top five deterrents. "Cycling to the destination takes less time than other modes" is only number five on the top ten motivator list. Winters et al. (2011) confirm that safety is more important than time for some people and feeling unsafe is definitely a strong deterrent to cycling. The consideration of safety cannot be ignored in modelling route choices of cyclists.

One of the drawbacks of revealed preference surveys in route choice studies, as highlighted in Stinson and Bhat (2003), is that the analyst needs to impute the routes considered by each respondent. These imputed routes might not resemble the actual routes considered by cyclists. Generating a realistic choice set is vital to the success of cyclist route choice modelling. A reasonable choice set should contain the chosen route and other reasonable routes not chosen. With the advancement in technology, it is possible to deduce the chosen route from large sample of GPS data (Menghini et al., 2010). The non-chosen routes in Menghini et al. (2010), however, are generated based on conventional single-objective routing methods which do not take into account the other factors identified to be relevant to route choice decisions of cyclists in their study, such as gradient, number of traffic signals, etc.

The contribution of this paper is to fill this knowledge gap by proposing a novel approach to overcome this problem. Bi-objective routing methods are applied to determine a realistic route choice set for both cyclists and potential cyclists. This route choice model can become an aid to promote cycling by allowing individuals to select a route they feel most comfortable with based on their own level of fitness and experience in cycling. This model can also become the building block of a comprehensive travel demand forecast model for cycle trips which is still missing in the literature and needs improvement in practice. Here, we extend preliminary results from Raith et al. (2009).

The paper is organised as follows: We first discuss methodology in Section 2 by introducing the two main objectives in cyclist route choice in Section 2.1, the problem is then formulated as a bi-objective routing problem in Section 2.2 and solution methods are presented in Section 2.4. We apply the proposed methodology to a case study in Section 3 and conclude with a discussion of future research topics in Section 4.

2. Methodology

Our modelling approach is developed based on the common observations that travel time appeared to have the most significant influence on route choice decisions of commuting cyclists (Aultman-Hall et al., 1997; Howard and Burns, 2001; Stinson and Bhat, 2003) and that other influencing factors such as safety and comfort (Stinson and Bhat, 2003) are also significant. Some cyclists prefer to travel longer distances in order to include cycle facilities on their routes (Krizek et al., 2007; Tilahun et al., 2007). In other words, the shortest route is not necessarily the most attractive route to a cyclist. There are numerous other factors that affect route choice. Some of these factors are subjective (such as physical fitness and value of time) and cannot be quantitatively assessed (Federal Highway Administration, 1992). Other factors such as motor traffic volume, presence of cycle facilities and topography are objective and can be observed (Aultman-Hall et al., 1997; Stinson and Bhat, 2003).

In our study, these objective factors are aggregated into the term *suitability*, a generic term that describes how suitable (e.g. safe and comfortable) a road is for cyclists. We, therefore, assume that cyclists have two objectives: (1) minimise travel time and (2) maximise level of suitability. Each link is characterised by these two attributes, i.e. travel time and its suitability rating. Subsequently, each route can be characterised based on its travel time and suitability attributes of each link along the route.

It is assumed that cyclists will choose a route over another only if the travel time is shorter without sacrificing the level of suitability, or if the level of suitability is higher without increase in travel time. A route is called *efficient* if, given the same travel time, there will be no route with higher level of suitability and given the same level of suitability, there will be no route with shorter travel time. For any given origin-destination pair, a set of efficient routes can be found.

We define the cyclists' choice set as the set of efficient routes. We believe that this is an adequate representation of the choice set for cyclists as it includes the shortest route as well as the route with highest suitability score, and the routes with best trade-off between time and suitability.

In the following, we will first describe how link and route characteristics can be assessed systematically in terms of the two objectives, namely travel time and suitability. Secondly, we will describe how the choice set, i.e. the set of efficient routes, is determined.

2.1. Formulation of route choice objectives

As outlined above, we model route choice based on two independent objectives, travel time and suitability. Both travel time and suitability need to be quantified for each link in the road network. We discuss how those criteria may be quantified in general.

2.1.1. Travel time objective

For vehicle traffic, the travel time on each link is approximated by a volume-delay function, e.g. a BPR function (Bureau of Public Roads, US Department of Commerce, Urban Planning Division, 1964), can be applied to determine the average travel time to traverse a link as a function of the traffic volume on this link. These functions are non-linear and depend on traffic volume to model congestion effects within the network. However, this is not applicable to cyclists, as they do not tend to wait in traffic queues, instead passing the queue on the inside. We make the assumption that cyclists travel with fixed velocity across the whole network. Therefore, a cyclist travel time function, which is based purely on distance, is assigned to the links of the road network. In reality, gradient also affects the speed of cyclists, and therefore their travel time. However, we choose not to include gradient in the travel time factor. As gradient is a major route choice factor for cyclists, we include it as part of the second objective of the model: Road gradient affects the suitability of a link negatively.

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 duration. In many road network models, intersections are represented by a single node with no additional delay, as shown in Fig. 1a. To account for the increased travel time, the intersections in the road network need to be modified.

Nodes in the road network that correspond to large, signalised intersections are modified to include additional nodes and links, as demonstrated in Fig. 1b. The travel times on these additional links represent directional delays at the intersection.

A realistic delay value needs to be calculated for the additional links. We suggest to estimate the average delay for signalised intersections as follows. Assuming that cyclists do not have to queue at traffic signals (due to their small size, they can manoeuvre through queues and get to the front relatively easily), the average time a cyclist spends at an intersection depends on the total duration of a signal cycle, S_t and the time the signals are red, R_t. A cyclist stop rate for each approach can be approximated as the proportion of the signal cycle that is red, R_t/S_t. The average delay for stopped cyclists can be represented as half the red time, $R_t/2$. Multiplying the cyclist stop rate by the average delay for stopped cyclists, gives the average delay for all the cyclists on each approach to the intersection as

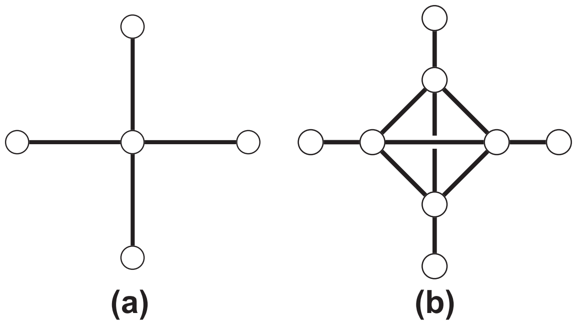

Fig. 1. Modification of intersection node layouts.

$$\text{average delay} = \frac{R_t^2}{2S_t}. \tag{1}$$

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. Of course, other measures of intersection delay may also be appropriate.

The travel time along a route, which consists of a sequence of consecutive links, can be computed by simply adding up link travel times. Therefore, $t(p)$, the total travel time along route p, is given by

$$t(p) = \sum_{i \in p} t_i, \tag{2}$$

where t_i is the travel time for the ith link of route p.

2.1.2. Suitability objective

In this section we describe how the suitability of a route can be evaluated. We first address methods to measure link suitability and then show how the suitability of a route can be calculated from the link suitabilities.

Following existing research, three main methods to assess link suitability have been identified. The methods proposed in two studies in the US (Harkey et al., 1998; Florida Department of Transportation, 2009) exclude some factors that we consider important for cyclists, such as road gradient. However, a study in the UK (Palmer et al., 1998) developed a comprehensive assessment method that evaluates a route's suitability against more factors than the two US studies.

In this study, we therefore adopt the method of Palmer et al. (1998) to systematically evaluate how suitable a link is for cyclists. This procedure allows suitability, a qualitative measure, to be assessed by a quantitative value. In total, 20 road factors are accounted for in this suitability rating system. Some of these are motor traffic volume, motor traffic speed, road lane width, presence of on-street parking, road gradient, percentage of heavy commercial vehicles, presence of cycle facilities (cycle lanes or shared bus/cycle lanes), pavement condition, etc. We note that the factors include many of the motivators and deterrents for the decision to cycle that are identified in Winters et al. (2011). These factors are used to derive a numerical score for each link. The factors considered by Palmer et al. (1998) should be adjusted based on locality (country and city) and what is common practice in an area.

As major intersections are modelled to account for intersection delay, it is also required to calculate a suitability value for these intersections. For example, a method from the United States rates the safety of intersections for bicycle through movement (Landis et al., 2003). To arrive at a suitability rating, this method considers lane widths, crossing distances, traffic volume, and the number of through lanes for a given approach. We adopt the method of Landis et al. (2003) to determine the suitability rating is determined for the through movements at all intersections. We also determine the suitability rating for turning movements based on the number of through lanes and the gradient of the approach to the intersection.

Unlike travel time, the suitability of a route cannot be represented by the sum of the suitability ratings of each link. Instead, we follow Palmer et al. (1998, p. 48) and propose to convert the suitability values of the links into a cumulative figure by considering the average suitability of the route for the entire duration of the trip (travel time). The suitability rating $s(p)$ along route p is thus given by

$$s(p) = \frac{\sum_{i \in p} t_i s_i}{t(p)}, \tag{3}$$

where $s(p)$ is the suitability score for the entire route p, s_i the suitability score for the ith link, $t(p)$ the total travel time for p, see (2), and t_i the travel time on the ith link.

The Palmer et al. (1998) method uses a scoring system to convert the scores to a simple A-F suitability rating, as shown in Table 1. In this way the suitability score of an entire route for cycling can be easily communicated to a cyclist.

2.2. Bi-objective routing

In bi-objective routing problems, instead of obtaining the shortest route between an origin-destination pair, the aim is to generate a set of compromise solutions, namely the efficient routes. As introduced at the start of Section 2, efficient routes are those, whose suitability level would not improve when trying to improve their travel time by switching to another route and vice versa. Fig. 2 shows possible travel time and suitability of different routes. In the figure, the travel time and suitability of efficient routes is marked by a diamond, whereas time and suitability of all other routes are indicated by a triangle. For every route marked by a triangle, there exists at least one efficient route, indicated by a diamond, with better value in both time and suitability.

Table 1
Scoring system for suitability objective.

Suitability score	81–100	61–80	41–60	21–40	1–20	$\leqslant 0$
Suitability rating	A	B	C	D	E	F

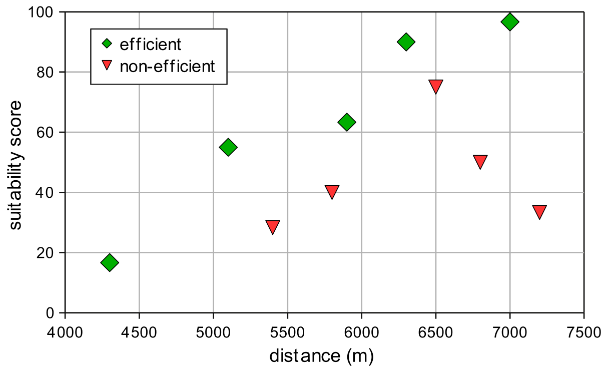

Fig. 2. Distance and suitability score of different paths.

We formalise these concepts in the following. Let $p = (i_1, i_2, \ldots, i_n)$ be a route consisting of the links with indices $i_1, i_2, \ldots, i_n$. By P we denote the set of all routes. The route p has travel time $t(p)$ and suitability level $s(p)$. Formally, route p is efficient if there exists no route $p' \in P$ such that

$$\begin{aligned} &t(p') < t(p) \quad \text{and} \quad s(p') \geqslant s(p) \text{ or} \\ &t(p') \leqslant t(p) \quad \text{and} \quad s(p') > s(p). \end{aligned} \tag{4}$$

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

In order to obtain all efficient routes between a given origin-destination pair, the relevant route choices for cyclists, a bi-objective routing algorithm is used. Before formally formulating and solving the cyclist route choice problem, we briefly introduce the related bi-objective shortest path problem.

2.3. The bi-objective shortest path problem

The bi-objective shortest path problem consists in finding efficient paths from an origin to a destination in a network according to two additive objectives that are both to be minimised. Note that in this section we use the term path rather than route, because this is commonly used in the literature. It can be formulated as follows:

$$\begin{aligned} \min \quad & c^1(p) = \sum_{i \in p} c_i^1 \\ \min \quad & c^2(p) = \sum_{i \in p} c_i^2 \\ \text{subject to} \quad & p \in P, \end{aligned} \tag{5}$$

where c_i^1, c_i^2 are two fixed costs associated with the ith link in the network. In (5) two additive cost functions have to be minimised simultaneously. It is well known that the bi-objective shortest path problem (5) is difficult to solve (formally, it belongs to the class of NP-hard problems (Serafini, 1986)) Moreover, it may have an exponential number of efficient paths (Hansen, 1979). However, numerical studies have shown that (5) can be solved quite efficiently, in particular in networks arising in practice such as road and rail networks, see Raith and Ehrgott (2009), Müller-Hannemann and Weihe (2006). Many algorithms to solve (5) use the idea of labelling. Labelling algorithms store lists of labels at each node of the network. These labels contain the cumulative values of the two cost functions, summed up along the links along a path from the origin to the node, as well as a predecessor, i.e. the previous node along the path. Throughout the algorithm, labels are selected and extended along links emanating from the node to which the label belongs to create new labels at the end node of the link. All dominated labels (a label at a node is dominated if there is another label at the same node with both cost values not worse and at least one strictly better) are eliminated and the algorithm terminates as soon as no further update is possible, guaranteeing that all efficient paths between origin and destination have been found. For details see Raith and Ehrgott (2009) and references therein. Labelling (and other bi-objective shortest path) algorithms work because the bi-objective shortest path problem satisfies the optimality principle which states that every sub-path of an efficient path (between any two nodes on the efficient path) is itself an efficient path between these nodes (see, e.g. Ehrgott, 2005).

With these preliminaries, we can now formulate the cyclist route choice problem as a bi-objective routing problem and discuss the difficulties it presents, how we overcome them, and present our solution approach.

2.4. Solving the cyclist route choice problem

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 suitability. From an individual cyclist's point of view, the most attractive route may well be slower than the fastest route, but have a higher suitability score. The bi-objective cyclist route choice problem is formally defined as the following mathematical optimisation problem

$$\begin{aligned} \min \quad & t(p) = \sum_{i \in p} t_i \\ \max \quad & s(p) = \frac{\sum_{i \in p} t_i s_i}{t(p)} \\ \text{subject to} \quad & p \in P. \end{aligned} \tag{6}$$

In the previous section we have seen that conventional bi-objective shortest path problems as in (5) are theoretically hard problems to solve. In the cyclist route choice problem (6) we face another difficulty, namely that the second objective of (6) does not satisfy the optimality principle stated for (5) in Section 2.3. We illustrate this in Example 1.

Example 1. Consider the network given in Fig. 3 with travel time t_i and suitability s_i shown alongside each link as (t_i, s_i).

The network contains two routes from the origin node 1 to the destination node 7: $p^1 = (i_1, i_7)$ and $p^2 = (i_2, i_3, i_4, i_5, i_6, i_7)$. We have $(t(p^1), s(p^1)) = (7, 13/7)$ and $(t(p^2), s(p^2)) = (6, 11/6)$, and hence both routes are efficient. However, comparing the sub-routes (i_1) and $(i_2, i_3, i_4, i_5, i_6)$ we see that they both have a suitablility of 2, whereas the former has a longer (i.e. worse) travel time (6) than the latter (5). Hence sub-route (i_1) of p^1 is not efficient.

The counterexample is significant, because it implies that the bi-objective problem (6) cannot be solved with bi-objective label-setting or label-correcting algorithms, the correctness of which relies on the optimality principle. We overcome this difficulty by applying the following theorem.

Theorem 1. *Let p^* be an efficient route of problem (6). Then p^* is also an efficient route of the following auxiliary bi-objective routing problem*

$$\begin{aligned} \min \quad & \sum_{i \in p} t_i \\ \max \quad & \sum_{i \in p} t_i s_i \\ \text{subject to} \quad & p \in P. \end{aligned} \tag{7}$$

Note that the auxiliary problem (7) is obtained by dropping the denominator of $s(p)$ in (6).

Proof. Let p^* be an efficient route in problem (6). Assume, contrary to the assertion, that p^* is not efficient for problem (7). Therefore, there exists a route p', that dominates p^* for (7). Then, by (4)

$$\sum_{i \in p'} t_i < \sum_{i \in p^*} t_i \quad \text{and} \quad \sum_{i \in p'} t_i s_i \geqslant \sum_{i \in p^*} t_i s_i \text{ or}$$
$$\sum_{i \in p'} t_i \leqslant \sum_{i \in p^*} t_i \quad \text{and} \quad \sum_{i \in p'} t_i s_i > \sum_{i \in p^*} t_i s_i,$$

which both imply that

$$\frac{\sum_{i \in p'} t_i s_i}{\sum_{i \in p'} t_i} > \frac{\sum_{i \in p^*} t_i s_i}{\sum_{i \in p^*} t_i}.$$

Therefore, p' dominates p^* for (6), a contradiction to p^* being an efficient solution of (6). □

The auxiliary problem (7) satisfies the optimality principle. However, the second objective function of (7) is a *longest route* objective (since suitability values are positive), and problem (7) has an infinite number of efficient routes containing circuits, because including circuits in a route improves the second objective function with every repetition of a circuit. Such circuitous

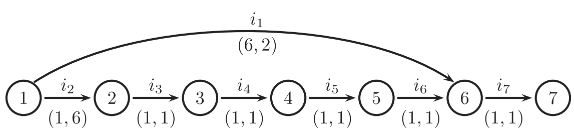

Fig. 3. Counterexample to the optimality principle.

routes are of course meaningless in the context of cycling. On the other hand, imposing that the routes may not contain circuits leads once again to a problem violating the optimality principle. In fact, the single objective longest route problem (without circuits) is itself already a very difficult NP-hard problem (Garey and Johnson, 1979) closely related to the travelling salesman problem.

We use a bi-objective near shortest path algorithm described in Raith and Ehrgott (2009) to solve the problem (7). This algorithm first finds the route with the shortest travel time, say τ. It then enumerates all routes that have a travel time between τ and $\tau + \delta$. If δ is sufficiently large, it is guaranteed that all efficient routes of (7) are found. Among the efficient solutions of (7) those that are not efficient solutions of (6) are eliminated and the efficient routes of (6) remain.

3. Case study

The model developed is applied to a case study in New Zealand. We analyse commuting trips in Auckland in the morning peak period, between a representative origin and destination in the Auckland city region, the shaded regions A (left) and B (right) in Fig. 4. 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 study area is also shown as an aerial map in Fig. 5.

The cycle network is obtained by modifying the simplified road network modelled in the ART (Auckland Regional Transport) model. The ART model road network consists of nodes, which correspond to large intersections, and links, that represent mid-block sections of major roads, see Davies et al. (2009). Additional links are added to the network in locations where only bikes are permitted, such as off-road cycle paths.

The link lengths are derived from the Geographic Information System coordinates of the nodes in the ART model road network. We assume a fixed velocity for cyclists across the whole network to derive travel times. 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 signalised intersections in the study area are coded to include directional links, then individually assessed to calculate

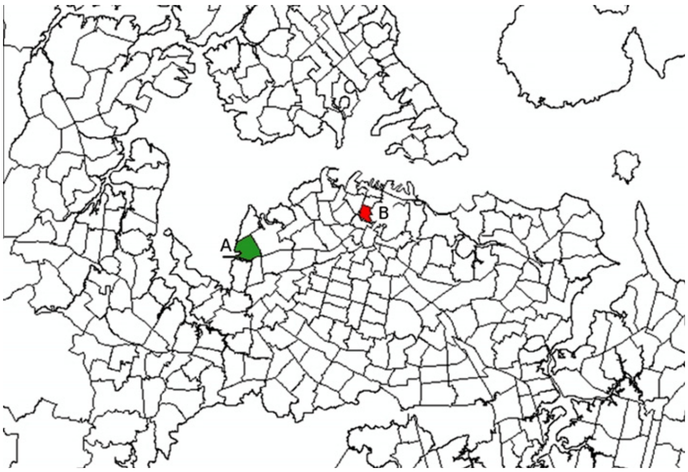

Fig. 4. Zone plan of Auckland Region in the Auckland Regional Transport Planning Model. *Source*: Auckland Regional Council.

Fig. 5. Efficient routes obtained in the case study. *Source of aerial map*: Auckland City Council.

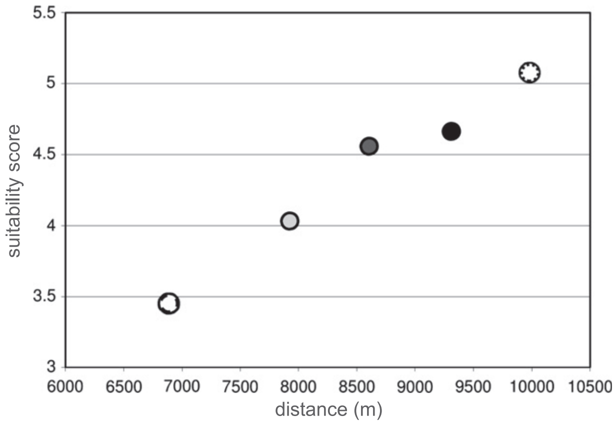

Fig. 6. Time and suitability of efficient routes.

the directional delays associated with each link. Link suitability is estimated for links representing roads using the method by Palmer et al. (1998). Suitability for additional links representing intersections is assessed following Landis et al. (2003) as described in Section 2.1.2.

The cyclist route choice problem (6) is solved as described in Section 2.4 and the efficient routes are obtained. Fig. 5 shows the efficient routes superimposed on an aerial map of the study area. It should be noted that while the black-and-white striped route (the top-most route) is the shortest one, most routes use at least part of the longer off-road cycleway parallel to the motorway (e.g. the gray and black routes).

The route distance and suitability score corresponding to the efficient routes are shown in Fig. 6. Each of the points on the graph represents the total travel time and suitability rating for an efficient route.

4. Discussion and suggestions for further research

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 incommensurable 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 bi-objective routing methods, by classifying factors influencing their decision into two categories, namely, travel time and suitability. Given an origin-destination pair, the model can be applied to identify the route choice set, i.e. the set of efficient routes, based on the criteria considered.

Our cyclist route choice model can be further developed into an intelligent tool to promote cycling. With further research, this model can also become a building block for a trip assignment model of cycle trips. The assignment model can then be applied to estimate cycling demand to support cycle facility investment decisions. The bi-objective routing model can also be the basis to model the assignment of cycle trips in a multimodal environment to support planning integration of cycling with public transport.

4.1. Intelligent cycling information system

A study in the UK found that regular cyclists form a very small minority of people who like cycling and hence will cycle under most circumstances (Gatersleben and Appleton, 2007). The majority of people have never contemplated cycling. This makes it a very challenging task to promote cycling. The concept of intelligent bicycle routing was introduced in the 1990s. Betz et al. (1993) suggests that to promote cycling, a sophisticated information system is needed, which should be able to provide accurate information on available routes, facilities, cycling opportunities and safety issues. Findings from Gatersleben and Appleton (2007) also indicate that there is a group of people who would like to cycle and could be persuaded to cycle under the right circumstances.

Maps can only provide limited information and the print medium precludes them from the provision of most up-to-date information. However, in this new era of advanced technology, the extensive use of cyberspace has enabled the provision of real-time information with sophisticated geographic information systems. This can be a means to induce changes in travel behaviour.

An intelligent cycling information system can be designed to induce behavioural change of particular groups. For example, Su et al. (2010) propose web based cycling route planner for Vancouver, Canada. Their system allows the cyclist to choose from compensatory and non-compensatory criteria identified in Winters et al. (2011), such as the least traffic pollution route, the least total elevation gain route, the most vegetated route, the shortest route, and routes with limits on the maximal gradient. However, while Su et al. (2010) consider multiple criteria, they do not consider them simultaneously,

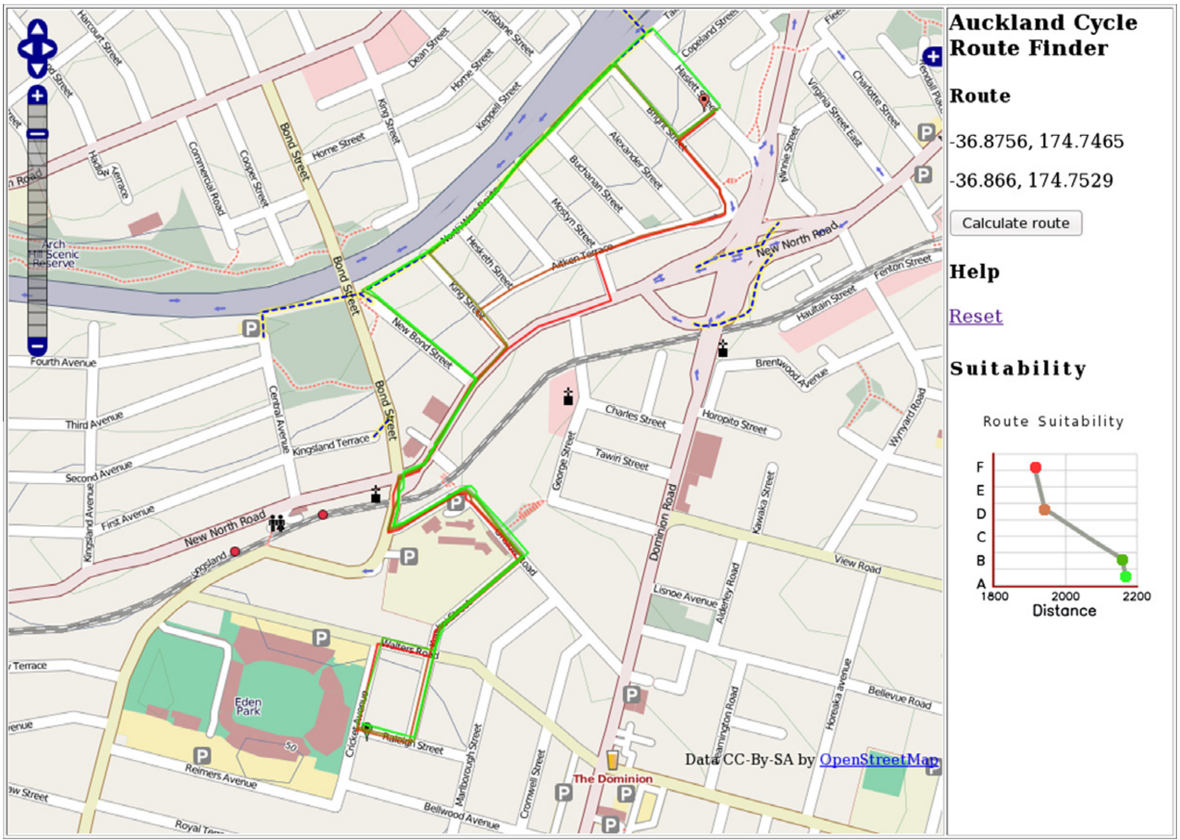

Fig. 7. The cycle route finder website.

the proposed routes always optimise a single criterion and do not allow compromise solutions, as is possible with our bi-objective routing methods.

The model proposed in this study can be developed into an intelligent cycle route planning system to promote cycling as a viable alternative to commuting by car. Given an origin-destination input by a user, the bi-objective routing model can be applied to determine a set of realistic efficient cycle routes. A user can then select the most appropriate route according to his/her level of competence. This information system can become an essential tool to promote cycling by providing comprehensive spatial information of the cycle network at a personalised level.

We have developed the prototype of a website that allows cyclists to obtain a set of efficient routes for the Auckland area, based on the network available from Open Street Maps.[1] Fig. 7 is a screen-shot of the prototype showing four different efficient cyclist routes between a residential street in the suburb of Kingsland and the stadium at Eden Park.

A study in Portland, Oregon, found that proximity to off-street cycle paths was not associated with higher level of cycling (Dill and Voros, 2007). Positive perceptions of the availability of cycle paths, however, was associated with more cycling and the desire to cycle more. In other words, the overall connectivity of the cycle network is a key to the success of promoting cycling.

From a planner's point of view, this can also be a valuable planning tool in identifying 'missing' links in a cycle network so that overall connectivity can be improved.

4.2. Comprehensive cycle demand forecast

Comprehensive route choice models do not exist for cycle trips, despite the well developed travel demand forecast models for other modes, i.e. private vehicles and public transport services. The models in the literature are mainly discrete choice models as discussed earlier. Others include models such as a simplified model using geographic information systems (Wigan et al., 1998), a simple regression model to estimate cycle trip rates (Barnes and Krizek, 2005), and a logistic regression model (Parkin et al., 2008).

[1] http://www.openstreetmap.org/.

One of the main benefits of promoting cycling comes from induced modal shifts, in particular from private vehicles. In New Zealand, this benefit is derived based on estimated demand elasticity values, assuming that the closer to the proposed cycling facility, the higher the probability of induced modal shift (New Zealand Transport Agency, 2010). A study in West Edinburgh, Scotland, found that cyclist facilities, primarily at the destination but also en route, largely determine the propensity to cycle to work or study (Ryley, 2006). This means that the procedure as adopted in New Zealand Transport Agency (2010) would have missed out the induced trips en route generated from origins beyond the assumed catchment area.

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. The bi-objective routing model developed in this study can be applied as a building block of a trip assignment model for cyclists. By applying the bi-objective routing method, we will be able to find the efficient routes 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, might choose the route with the highest suitability rating, which is also the longest route. Further research is required to develop an assignment method to assign the cyclists to their preferred route. In this way, this will enable network analysis of all cycle trips. Hence, the usage of proposed cycling facilities can be estimated. Most importantly the cost and benefits of different improvement schemes can be evaluated in a comprehensive manner to inform policy decisions and projects can be prioritised accordingly.

4.3. Integration of cycling with public transport

Bike-and-ride, or the combined use of bicycle and public transport for one trip, is considered to be a more sustainable transport solution Martens (2007) than driving. In fact, integration of cycling with public transport is one of the successful policies in bicycle friendly countries such as The Netherlands and Denmark (Pucher and Buehler, 2008). Bike-and-ride might not be a popular option for cyclists today in cities such as Auckland. With continuous improvement in public transportation services, we might be able to make bike-and-ride a viable option in the future. For example, in Auckland, promoting cycling to railway stations, park-and-ride facilities along the Northern Busway, a dedicated bus lane following a motorway, can certainly promote the use of rail and bus services. Cycle paths can be planned as feeder routes for bike-and-ride. With further research, the travel demand for bike-and-ride can be analysed with a multiobjective multimodal trip assignment model.

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References

Akar, G., Clifton, K.J., 2009. Influence of individual perceptions and bicycle infrastructure on decision to bike. Transportation Research Record 2140, 165–171.

Antonakos, C.L., 1994. Environmental and travel preferences of cyclists. Transportation Research Record 1438, 25–33.

Auckland City Council, 2007. Auckland City Council's Cycling and Walking Framework. <http://www.aucklandcity.govt.nz/auckland/Transport/bikes/docs/cyclingwalkingf1.pdf> (accessed 20.09.10). .

Aultman-Hall, L., Hall, F.L., Baetz, B.B., 1997. Analysis of bicycle commuter routes using geographic information systems: implications for bicycle planning. Transportation Research Record 1578, 102–110.

Barnes, G., Krizek, K., 2005. Estimating bicycling demand. Transportation Research Record 1939, 45–51.

Betz, J., Dustrude, J., Walker, J., 1993. Intelligent bicycling routing in the United States. Transportation Research Record 1405, 21–27.

Bovy, P.H.L., Bradley, M.A., 1985. Route choice analyzed with stated-preference approaches. Transportation Research Record 1037, 11–20.

Bureau of Public Roads, US Department of Commerce, Urban Planning Division, 1964. Traffic Assignment Manual for Application with a Large, High Speed Computer.

Davies, J., Valero, J., Young, D., 2009. The Auckland Transport Models project: overview and use to date. The 32nd Australasian Transport Research Forum, held in Auckland, New Zealand. .

Dill, J., Carr, T., 2003. Bicycle commuting and facilities in major US cities: if you build them, commuters will use them. Transportation Research Record 1828, 116–123.

Dill, J., Voros, K., 2007. Factors affecting bicycling demand: initial survey findings from Portland, Oregon. Transportation Research Record 2031, 9–17.

de Dios Ortúzar, J., Willumsen, L., 2001. Modelling Transport, third ed. John Wiley & Sons, Chichester.

Ehrgott, M., 2005. Multicriteria Optimization, second ed. Springer Verlag, Berlin.

Federal Highway Administration, 1992. Case Study No. 1: Reasons Why Bicycling and Walking Are Not Being Used More Extensively as Travel Modes. Technical Report FHWA-PD-92-041, US Department of Transportation.

Florida Department of Transportation, 2009. Quality/Level of Service Handbook. <http://www.dot.state.fl.us/planning/systems/sm/los/pdfs/2009FDOTQLOS_Handbook.pdf> (accessed 20.09.10). .

Garey, M.R., Johnson, D.S., 1979. Computers and Intractability – A Guide to the Theory of NP-Completeness. Freeman, San Francisco, CA.

Gatersleben, B., Appleton, K.M., 2007. Contemplating cycling to work: attitudes and perceptions in different stages of change. Transportation Research Part A 41, 302–312.

Hansen, P., 1979. Bicriterion path problems. In: Fandel, G., Gal, T. (Eds.), Multiple Criteria Decision Making Theory and Application. Springer Verlag, Berlin, pp. 109–127.

Harkey, D.L., Reinfurt, D.W., Knuiman, M., 1998. Development of the bicycle compatibility index. Transportation Research Record 1636, 13–20.
Hopkinson, P., Wardman, M., 1996. Evaluating the demand for cycle facilities. Transport Policy 3, 241–249.
Howard, C., Burns, E.K., 2001. Cycling to work in phoenix: route choice, travel behavior and commuter characteristics. Transportation Research Record 1578, 39–46.
Hunt, J.D., Abraham, J.E., 2007. Influences on bicycle use. Transportation 34, 453–470.
Krizek, K.J., El-Geneidy, A., Thompson, K., 2007. A detailed analysis of how an urban trail system affects cyclists' travel. Transportation 34, 611–624.
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.
Lindsay, G., Macmillan, A., Woodward, A., 2011. Moving urban trips from cars to bicycles: impact on health and emissions. Australian and New Zealand Journal of Public Health 35, 54–60.
Lingwood, P., 2004. Promoting walking and cycling as an alternative to using cars: perception of safety is biggest obstacle. British Medical Journal 329, 1237.
Martens, K., 2007. Promoting bike-and-ride: the Dutch experience. Transportation Research Part A 41, 326–338.
Menghini, G., Carrasco, N., Schüssler, N., Axhausen, K.W., 2010. Route choice of cyclists in Zürich. Transportation Research Part A 44, 754–765.
Morris, J.N., 1994. Exercise in the prevention of coronary heart disease: today's best buy in public health. Medicine & Science in Sports & Exercise 26, 807–814.
Müller-Hannemann, M., Weihe, K., 2006. On the cardinality of the Pareto set in bicriteria shortest path problems. Annals of Operations Research 147, 269–286.
de Nazelle, A., Rodríguez, D., Crawford-Brown, D., 2009. The built environment and health: impacts of pedestrian-friendly designs on air pollution exposure. Science of the Total Environment 407, 2525–2535.
New Zealand Transport Agency, 2010. Economic Evaluation Manual – vol. 2. <http://www.nzta.govt.nz/resources/economic-evaluation-manual/volume-2/docs/eem2-jan2010.pdf> (accessed 20.09.10). .
Ogilvie, D., Egan, M., Hamilton, V., Petticrew, M., 2004. Promoting walking and cycling as an alternative to using cars: systematic review. British Medical Journal 329, 763.
Palmer, D., Ai-Uzaizi, E., Campbell, J., Killips, S., Lawson, V., Reid, S., Lee, J., Mason, S., McLoughlin, T., Noble, P., Philippou, P., Russell, T., Sabey, B., 1998. Guidelines for cycle audit and cycle review. Published by The Institution of Highways & Transportation. .
Parkin, J., Wardman, M., Page, M., 2008. Estimation of the determinants of bicycle mode share for the journey to work using census data. Transportation 35, 93–109.
Pucher, J., Buehler, R., 2008. Cycling for everyone: lessons from Europe. Transportation Research Record 2074, 58–65.
Raith, A., Ehrgott, M., 2009. A comparison of solution strategies for biobjective shortest path problems. Computers & Operations Research 36, 1299–1331.
Raith, A., Van Houtte, C., Wang, J.Y.T., Ehrgott, M., 2009. Applying bi-objective shortest path methods to model cycle route-choice. In: ATRF 2009 Proceedings. .
Ryley, T., 2006. Estimating cycling demand for the journey to work or study in West Edinburgh, Scotland. Transportation Research Record 1982, 187–193.
Serafini, P., 1986. Some considerations about computational complexity for multi objective combinatorial problems. In: Jahn, J., Krabs, W. (Eds.), Recent Advances and Historical Development of Vector Optimization. Springer Verlag, Berlin, pp. 222–232.
Shafizadeh, K., Niemeier, D., 1997. Bicycle journey-to-work: travel behavior characteristics and spatial attributes. Transportation Research Record 1578, 84–90.
Statistics New Zealand, 2008. Main means of travel to work for the employed Cebsus usually resident population, ages 15 years and over. Technical Report, Statistics New Zealand. .
Stinson, M.A., Bhat, C.R., 2003. Commuter bicyclist route choice: analysis using a stated preference survey. Transportation Research Record 1828, 107–115.
Su, J.G., Winters, M., Nunes, M., Brauer, M., 2010. Designing a route planner to facilitate and promote cycling in Metro Vancouver, Canada. Transportation Research Part A 44, 495–505.
Tilahun, N.Y., Levinson, D.M., Krizek, K.J., 2007. Trails, lanes, or traffic: valuing bicycle facilities with an adaptive stated preference survey. Transportation Research Part A 41, 287–301.
Wardman, M., Tight, M., Page, M., 2007. Factors influencing the propensity to cycle to work. Transportation Research Part A 41, 339–350.
Wardrop, J.G., 1952. Some theoretical aspects of road traffic research. Proceedings of the Institution of Civil Engineers, Part II 1, 325–362.
Wigan, M., Richardson, A.J., Brunton, P., 1998. Simplified estimation of demand for nonmotorized trail using geographic information system. Transportation Research Record 1636, 47–55.
Winters, M., Davidson, G., Kao, D., Teschke, K., 2011. Motivators and deterrents of bicycling: comparing influences on decisions to ride. Transportation 38, 153–168.