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Prioritising cycle infrastructure projects

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Abstract

Walking and cycling are becoming more important modes of transport in the cities of the developed world in view of increasing traffic congestion, oil prices, and increasingly due to environmental awareness. This paper deals with the improvement of cycling infrastructure applied to the Auckland (NZ) region. Construction of proposed cycle infrastructure needs to be phased and requires a means for prioritising projects over time. The existing project selection method uses benefit to cost ratios (BCRs), with high BCR projects prioritised on the basis of a simple rank order. Estimated usage over the life of the cycling infrastructure is a major component of the BCR computation; hence demand forecasting is crucial in this analysis. We present a new demand forecasting model to be used within the existing prioritisation framework. It may, however, be beneficial to prioritise construction of a low BCR project in order to increase connectivity of the cycle network as a whole. We call this the project bundling or portfolio effect. The new demand forecasting method allows us to estimate demand (and hence benefit) of individual projects and also additional benefits derived from project interdependencies. We furthermore propose a project selection method that appropriately models these interdependencies rather than selecting projects based on BCR ranking of individual projects only. We present a case study demonstrating this selection methodology. For road and cycleway controlling authorities with budget constraints, our methodology provides a cycleway project selection and prioritisation approach based on whole network benefits, rather than on an individual project basis.

1. Introduction

The issue of global warming has assumed significant proportions in the world today. Great concern surrounds the large quantities of greenhouse gases such as carbon dioxide which are trapping infrared radiation in our atmosphere. Recent studies have shown that the carbon dioxide that is produced globally from the burning of fossil fuels such as petrol, diesel and ethanol is increasing by three percent every year (World Resources Institute 2010). Considering that one of the main users of such fossil fuels are automobiles, sustainable alternative modes of transportation that do not rely on fossil fuels must be promoted in order to help address issues relating to global warming.

The New Zealand Transport Agency (NZTA) promotes active modes of transport such as walking and cycling. Not only do these modes have atmospheric benefits, but they are also believed to alleviate congestion, help improve travel times for all road users and improve the reliability and resilience of the transport networks (NZ Transport Agency 2009). Additionally, there are also clear health benefits for individuals who adopt these physically active modes of transport.

In 2008, NZTA set a target to double walking and cycling modes of transport from 15% to 30% of total trips by 2040 within the Auckland urban and peri-urban areas (Hinton & Teh 2008). In the case of cycling this was to be achieved primarily by the addition of cycling facilities to state highways (over which NZTA has control) throughout Auckland. Potential cycling infrastructure development projects are proposed and analysed throughout several regions in Auckland. However, implementing all of these proposed projects is not feasible given budget constraints, and therefore needs to be prioritised over several years. The aim of this research is to provide a methodology to help prioritise cycling projects within the

Auckland region in selecting those projects that are most beneficial to the cycling infrastructure network. To achieve this we propose an improved portfolio selection method that overcomes potential flaws in the current method.

At the core of any method to select a portfolio of projects is an appropriate methodology to estimate cost of individual projects and groups of projects as well as their benefits. Estimating benefit depends on correct estimation of the usage of a new piece of infrastructure. We present a novel approach for estimation of the usage of cycling infrastructure that takes into account how the new piece of infrastructure fits into the existing network and also how it links into other new infrastructure.

The presented approach is inspired by and applied to cycling infrastructure projects in Auckland, New Zealand, but we believe that the underlying methodology is also valid and applicable to cycling infrastructure developments in other geographic locations. Additionally, we believe that this approach may be applicable to other project prioritisation problems where there are value-adding benefits to be derived from developing a network (such as transport and communication).

This article is organised as follows. In Section 2 we introduce the current approach to selecting cycling infrastructure projects and discuss possible weaknesses. We propose a new methodology to this selection process in Section 3. This new methodology is twofold. We first propose a novel approach to estimating how many cyclists will use a new section of cycling infrastructure. Then, we propose an Operations Research model for the selection of cycling projects that takes interconnectivity between different projects within a road and cycling network into account. In Section 4, a case study is presented to demonstrate the application of this new methodology. We conclude and discuss future work in Section 5.

2. Discussion of a current cycling project prioritisation approach

Before we introduce the new demand forecasting and portfolio selection methodology that was developed to prioritise cycling projects in Section 3, it is necessary to first explore the details of current techniques used by NZTA. We also illustrate some weaknesses in this approach.

In accordance with the Auckland Region Walking and Cycling Strategy (Hinton & Teh 2008), NZTA officials along with representatives from the Auckland Regional Transportation Authority (ARTA) developed a list of over 70 proposed cycling projects within the Auckland region in 2008. The evaluation of those proposed projects follows the methodology described in Chapter 8 of Volume two of the Economic Evaluation Manual (New Zealand Transport Agency 2010). In the following we outline the components of this evaluation process targeted at deriving each cycling facility's benefit to cost ratio (BCR).

2.1 Benefit to cost ratio

The main component of the economic evaluation of a new facility is a BCR calculation. The BCR value is crucial when determining the feasibility of a project and determines whether a proposed project should proceed to later stages in the evaluation process. The BCR for a new facility is defined as the ratio of its benefit over its cost:

$$\mathrm{BCR(facility)} = \frac{\mathrm{Benefit(facility)}}{\mathrm{Cost(facility)}}.$$

Both benefit and cost are expressed in monetary terms based on the Consumer Surplus Methodology (New Zealand Transport Agency 2010). Here, each type of benefit that a new facility will produce is monetised according to a consumer's willingness to pay for each identified benefit. Among the benefits that are monetised in the BCR calculation of a cycling project are: travel time savings, vehicle operating savings, crash cost savings, seal extension savings, carbon dioxide savings and other tangible savings. Vehicle operating or carbon dioxide savings, for example, are derived from the number of users of motorised vehicles that switch their transport mode to cycling due to the construction of a new cycling facility. Other intangible savings that cannot be easily monetised are not included in the evaluation.

Two main cost components of a new facility are considered in the BCR calculations, namely capital and maintenance costs. Capital costs are expenses incurred to bring the cycling facility to a commercially appropriate standard while maintenance costs are incurred in the day to day running of a facility.

2.2 Demand forecast

Travel time, the vehicle operating, and carbon dioxide savings mainly depend on the demand forecast for a new facility. Since this demand forecast is such an important component of the benefit calculation, it is essential to fully understand how demand is estimated. Users of a new cycling facility can be divided into two categories: existing cyclists and new cyclists.

Existing cyclists are already frequent cyclists who are expected to use a facility if it is constructed close to where they live or work. In the current estimation procedure, the existing cyclists are estimated using observational data, i.e. current cyclist numbers are obtained in manual counts. For a new facility, when counting is impossible as the facility does not yet exist, estimates are based on available counts close to the location of the new facility.

New cyclists are those who will change from another mode of transport to cycling due to the construction of the new facility. These new cyclists are made up of new commuter cyclists (who cycle as a mode of transportation to work) and new other cyclists (who cycle for other purposes, e.g. recreation). In the NZTA method the numbers of new cyclists for a facility are estimated using the so-called “Buffer Zone” method, as described in Krizec et al. (2007). Buffer Zones with certain fixed radii are drawn around a proposed cycling facility. The number of new cyclists is then estimated based on population density and distance to the facility within the different Buffer Zones according to fixed factors. Hence, whether the facility is used by new cyclists is assumed to depend only on the area of the Buffer Zone and the population within it. An allowance may be made for cyclists travelling through a zone who originate from outside the buffer zone, but this is not formalised in the current method.

Thus the current estimation of existing and new cyclists does not take into account how it links into an existing network of cycling facilities.

2.3 Current portfolio selection method

In this section we briefly outline NZTA’s current method of selecting a portfolio, i.e. selecting some of the proposed cycling projects. It should be noted that this method was developed in 2008 and is currently being updated.

Stages 1 and 2 (Identification and Consultation): These stages involve listing all possible cycling projects. There is also a consultation with Auckland’s local authorities and Auckland Transport (who replaced the former ARTA).

Stage 3 (Assessment): All projects are ranked according to several assessment criteria, such as connectivity to the passenger transport network. A score is derived based on a simple attribute ranking technique of qualitative features to obtain the initial ranking.

Stage 4 (Ranking and Urgency): The projects from the consultation stage are additionally tagged as urgent (U), under investigation (I) or pending (P) depending on their urgency.

Stage 5 (Prioritisation): A shortlist of projects is determined based on the assessment scores and urgency levels.

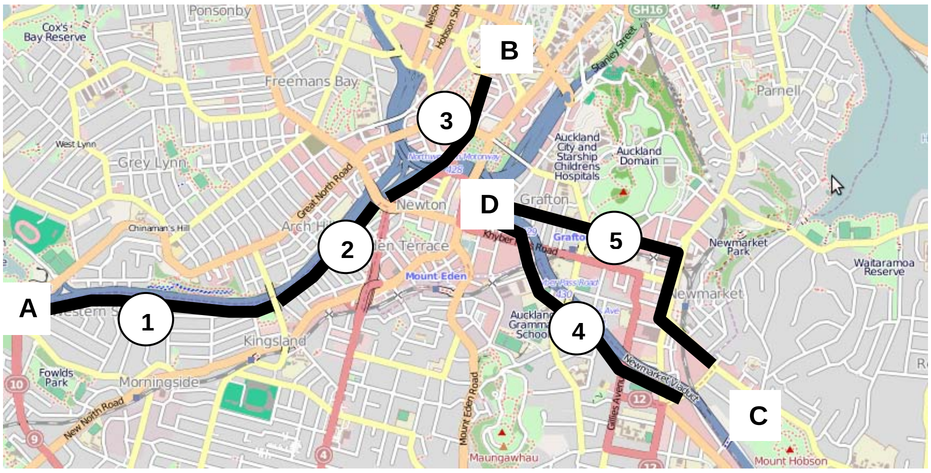
Stage 6 (Feasibility and Selection): In this stage, for each of the shortlisted projects, the benefits, costs and hence the BCRs are determined. The list of projects is then ranked according to the largest to smallest BCR values. A final portfolio of projects is selected for implementation by choosing the projects with the largest BCRs within the constraints of the cycling budget i.e. the projects are prioritised using a simple rank order.

2.4 Weaknesses in current portfolio selection method

Analysis of NZTA’s current portfolio selection method highlights some limitations that should be addressed in order to obtain a more formalised quantitative portfolio selection method. The initial stages are deemed appropriate as they combine an efficient process for initial filtering with expert opinion to score the assessment criteria. The main weaknesses arise in Stages 5 and 6 of the current method and are as outlined below.

The first main weakness that is found in the current methodology is the approach used to forecast the demand. Both the observational data used to forecast the number of existing cyclists and the Buffer Zone method used to forecast the number of new cyclists are not particularly accurate and do not truly represent the number of cyclists expected to use a facility. As outlined in Section 2.2 the number of existing cyclists, who already use their bikes as mode of transport, is based on counts. Whenever a facility is to be newly constructed, one cannot of course count cyclists on this non-existing facility, so a rough estimate is made based on counts around the facility, when available. When estimating new cyclists, the Buffer Zone method may forecast a larger number of cyclists when analysing two paths that are close to each other (such as paths 4 and 5 in Figure 1) as the buffer zones overlap. This is because the two cycle paths share a lot of their demand as they are geographically close. Furthermore, it is likely that new cyclists do not only come from within the Buffer Zone. For example, this may happen when a new cycling facility lies along a possible route of a daily commute to work with origin and destination of the trip outside the considered Buffer Zone. As mentioned above, the number of cyclists that are estimated to use a new facility is a large contributor to the benefits for a facility and thus must be estimated as accurately as possible.

Figure 1: Potential cycling projects. Background image: OpenStreetMap (2011)



Another major weakness is that the current methodology does not capture interdependencies between different potential projects. While benefits, costs and the BCR are calculated for all individual projects in Stage 6, there is no quantitative investigation into project bundling, i.e. the benefit or dis-benefit of placing two or more projects in conjunction with each other. While there may be an attempt to consider these interdependencies in Stage 5 (i.e. “urgent” projects potentially are those which could provide missing network links), there is currently no formalised method of modelling this. Let us consider two scenarios to demonstrate this point.

Figure 1 shows a map of the central Auckland region and five potential proposed cycling projects in the area which are labelled 1 to 5. To cycle from point A to somewhere in the city centre (point B) one would follow the three cycle paths 1, 2, and 3. Let us assume the first two proposed projects have a high BCR (since they may be relatively inexpensive to construct and have a high benefit), but project 3 has a lower BCR (since it may be expensive to construct due to a more challenging location but still have a high benefit). Using the current methodology, both high BCR paths may be selected. However, project 3, which has a low BCR, may not be selected due to budget constraints. Thus points A and B are not connected as project 3 is missing. As B represents the city centre a crucial element of the cycling network, that would connect outer suburbs to the city centre, is missing. While the BCR of project 3 is low when considered as a stand-alone project, a possible additional benefit due to increased network connectivity, when project 3 is constructed in conjunction with projects 1 and 2, is neglected. Network connectivity is not measured by the current method, as BCRs are only derived for individual projects without taking connectivity into account when assessing benefit. We conclude that the importance of missing links may not be addressed adequately in the current method.

Now consider a different scenario also illustrated in Figure 1. Assuming one would want to travel from the area of the map around point C to the area around D, there are two alternative projects providing cycling facilities of similar length. Here we see that between points C and D we have two potential cycle projects that run almost in parallel. Assuming both projects have a high BCR (since they may be relatively inexpensive to construct and have a high benefit), using the current methodology, both of these paths might be selected. This may not be a desirable solution, as constructing almost parallel pieces of cycling infrastructure close to each other in a fairly sparse cycling network may be a waste of resources, which could be better invested elsewhere to improve connectivity in the cycling network. This illustrates how unnecessary duplication in the network should be avoided within the methodology. Again, the BCR score computation should take into account possible negative effects on BCR scores if more than one project is implemented.

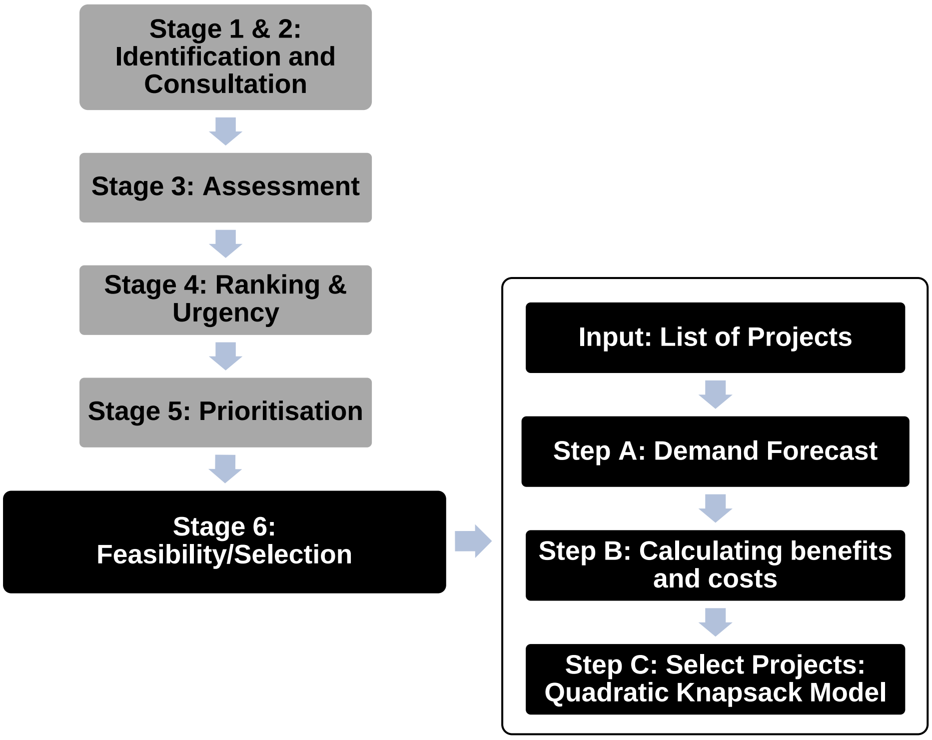
The third weakness is the usage of a simple rank order for selecting projects. Using a simple rank order will lead to the selection of the first few projects until the budget capacity is reached. A different combination of projects may exist that is feasible with respect to the available budget while achieving a higher overall benefit. This is a known weakness of simple rank order methodologies, which are therefore often referred to as heuristic approaches (eg Hartman, 2007). Nevertheless, they are commonly used in practice due to their simplicity.

While the scenarios discussed above are of course somewhat simplistic illustrations (and screening by an intelligent person would certainly be part of the decision making process), they demonstrate the limitation of only considering BCRs of individual projects. The examples also illustrate the need to not look at projects in isolation but rather consider them as part of a wider network of cycling infrastructure. In practice, the number of considered projects is much higher than in the example given above, making manual screening and identifying relationships between projects more difficult than in the given example. We furthermore pointed out the weakness of using a simple rank order of BCRs for portfolio selection. Thus we suggest a more formalised approach in the following that takes into account network connectivity and BCRs of pairs of projects.

3. New portfolio selection method

Given that the main weaknesses of the current methodology have been established, a new portfolio selection method which addresses these issues must be developed. We propose to leave Stages 1 – 5 unaltered as they primarily involve listing potential projects and providing a preliminary urgency ranking. We explore changes to the feasibility and selection stage (Stage 6), where from the list of urgent projects, a portfolio of projects to be implemented is selected. We have developed a new portfolio selection method as outlined in Figure 2. Given a list of projects as an input from Stage 5, we propose a new demand forecast methodology in Step A. Then benefits and costs are derived using the conventional approach in Step B. Finally, Step C deals with the selection of a portfolio of projects which is based on a quadratic knapsack optimisation problem rather than a simple rank order. We now give a detailed description of these steps.

Figure 2: New portfolio selection method with new demand forecast methodology.



3.1. Demand forecast methodology (Step A)

We identified a potentially inadequate demand forecast in Section 2.4. One aspect was that network effects are not taken into account at all, i.e. the effect of building a strategic, but expensive, piece of infrastructure that provides an important link in the cycling network is not formally taken into account when calculating benefits as this is not taken into account when calculating cycle facility usage (demand). The following describes how this weakness may be overcome.

The new methodology we suggest is dedicated to obtaining forecasts for demand (or usage) of individual projects and for different combinations of projects. The reason for considering combinations of adjacent projects is because this is where the interdependency flaw is overcome. By forecasting demand and deriving the BCRs for projects alone and when they are built in conjunction with each other, we can identify the benefit or dis-benefit of projects implemented together. The basis for this facility (or project) demand estimation is that we can estimate the demand (or usage) of a facility that is inserted into an existing road network using what we call a cyclist assignment algorithm, which will be described in the following.

Firstly, a representation of the road network surrounding the location of proposed cycling infrastructure projects must be obtained. This network includes all pieces of infrastructure which may be used by bicycles. All existing cycle paths are included, but motorways for example are excluded. The proposed cycling infrastructure is also added to the network.

A demand matrix based on an available survey or statistical data is also derived. This contains an estimate of the total number of cyclists wanting to travel between all pairs of different zones (i.e. possible origins and destinations) within the road network. From the demand matrix we derive an estimate of the number of existing cyclists that can be expected to use a proposed cycle facility which we call the demand forecast of the facility, (not to be confused with the demand matrix). In the following we discuss how to determine a demand forecast for each shortlisted cycle facility in the network.

Cyclist assignment algorithm to forecast demand of the facility by existing cyclists

Once the network and the demand matrix are obtained the cyclists' travel routes through the network from their origins to their destinations are determined. We propose an approach similar to the traffic assignment method for vehicular traffic in road networks (e.g. Ortúzar & Willumsen 2002).

We use an algorithm developed for this research that performs this *cyclist assignment* to estimate the number of existing cyclists on each of the roads within the network. Inspired by traditional traffic assignment approaches, we identify routes a cyclist is likely to travel and then assign portions of the demand to the roads that make up this route. Based on previous research, the route choice of cyclists is assumed to depend on the travel time (or distance along a path) and the suitability of a route for cycling (e.g. Aultman-Hall et al. 1997, Stinson & Bhat 2003). By suitability we mean an aggregate measure that combines safety aspects with other considerations such as slope and surface quality that make a particular road (or cycle path) more or less suitable for cycling. For example a cycle path that was purpose built for cyclists and has no access for motorised vehicles is considered more suitable for cycling than a shared busy or even congested main road.

In the following we outline the concept of the route choice model proposed in Raith et al. (2009) that takes into account both travel time and suitability of a route. It is assumed that a cyclist prefers a route R with *minimal overall distance*

$$d(R) = \sum_{l \text{ is link in route } R} d_l$$

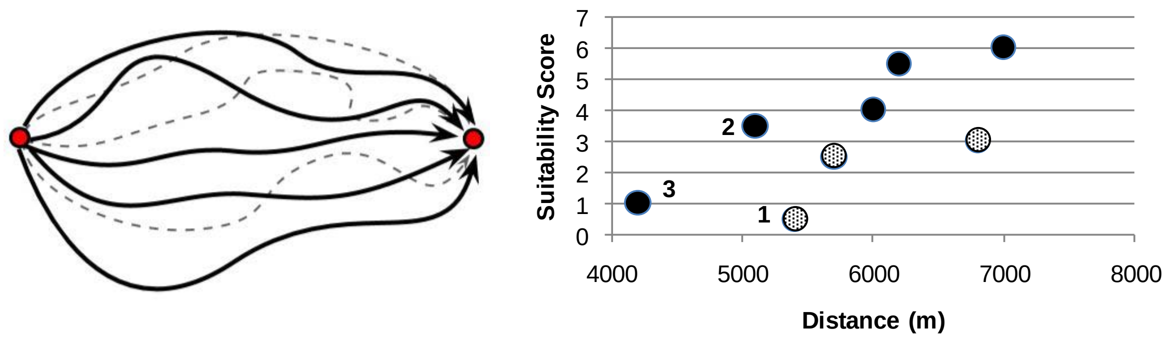
but also with *maximum distance-weighted suitability score*

$$s(R) = \sum_{l \text{ is link in route } R} s_l \times d_l.$$

Here d_l is the length of a link and s_l is its suitability score. Raith et al. (2009) describe how a suitability score s_l can be derived. Typically a minimum-distance path will have a fairly low suitability score $s(R)$ as the most direct route is unlikely to use many dedicated cycling facilities or quiet roads. On the other hand, a route with high suitability score is likely to be longer, as the cyclist may have to take some detours to be able to use dedicated cycling facilities (which may be rather sparsely distributed). The resulting route choice problem has two conflicting objectives, making it a bi-objective route choice problem. When solving this bi-objective route choice problem we aim to find a set of *efficient* routes (or paths) between two points in a network, where two route choice objectives, in our case $d(R)$ and $s(R)$, are considered. A route R is called efficient if there is no other route S with distance less than or equal to that of R and suitability at least as high as that of R, and S is truly better than R in either distance or suitability at the same time.

Consider the example shown in Figure 3 below. Here it is assumed that, between the source and destination nodes as shown on the left of the figure, there are a total of eight possible paths. The five solid black paths are the efficient paths according to the definition given above, whereas the three gray dotted paths are the non efficient paths and are those which can be improved both according to their suitability and distance. To demonstrate this, consider solution 1 in the graph. This is not an efficient solution as other solutions exist with both higher suitability and lower distance, such as solutions 2 and 3. All other gray dotted paths in the graph can also be improved in a similar manner. The solid black points in the graph represent efficient paths.

Figure 3: Example efficient paths.



Efficient paths are shown in black, non-efficient paths are dotted

A problem related to this bi-objective route choice problem, that is well known in the Operations Research literature, is the bi-objective shortest path (BSP) problem. This differs from the problem above in having two *minimisation* objectives (e.g. Martins 1984). Here, we transform the suitability objective into a un-suitability objective $u(R)$ that can be minimised $u(R) = \sum_{l \text{ is link in route } R}(S_{\max} - s_l) \times d_l$, where $S_{\max}$ is the maximum possible suitability score. This bi-objective shortest path (BSP) problem is a natural extension of the single-objective shortest path problem which has been widely studied (e.g. Cherkassy et al. 1996).

We now assume that all cyclists will choose one of the efficient routes (or paths) of the BSP problem but recognise that two different individuals may choose different paths depending on how comfortable they are cycling along, for example, busy streets that may not be perfectly suited for cycling. We now outline the algorithm for the cycling assignment for a given road and cycling network.

Outline of cyclist assignment algorithm:

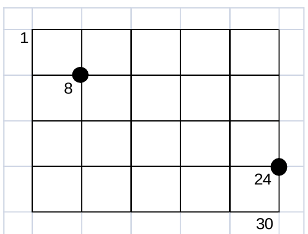
1. *Input: cycle demand matrix, road network*
2. *For each origin-destination (OD) pair in the demand matrix, do the following:*
   2.1. If the source node and destination node are not the same, do the following:
      2.1.1. Set the source node, destination node and the demand for this pair.
      2.1.2. Use the BSP Algorithm to find the set of efficient routes from the source node to the destination node.
      2.1.3. Determine the flow on each efficient route by distributing demand evenly *amongst all efficient paths. Calculate the resulting number of cyclists on each link in the network.*

A BSP Algorithm to use in Step 2.1.2 is for example the BSP label setting algorithm (Raith & Ehrgott 2009).

In order to illustrate how this algorithm works, it is useful to observe a simple example. The following example demonstrates the cycling assignment algorithm for one origin-destination (OD) pair.

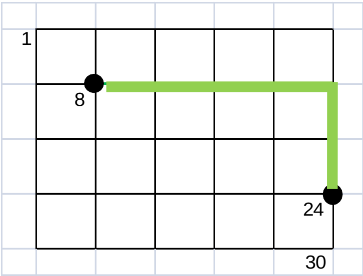
Cycling assignment algorithm example:

2.1.1 origin node = 8, destination node = 24, demand = 3.

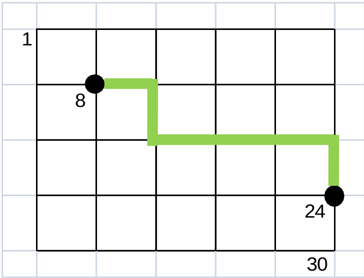


2.1.2 Assume that the routes highlighted below are the efficient routes:

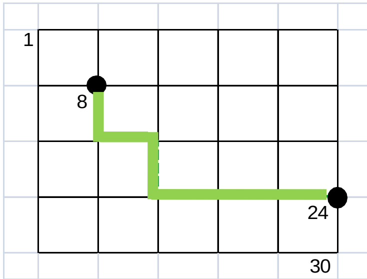
Route 1:



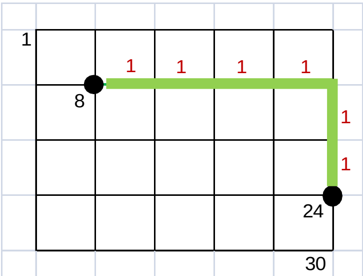
Route 2:



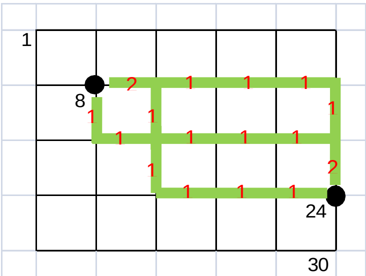
Route 3:



2.1.3 There are 3 efficient routes; therefore demand on each route is 3 / 3 = 1. If we look at efficient route 1, this cyclist demand of 1 is applied to each link.



After applying the corresponding demand to each route, the resulting total number of cyclists on each link of the network is shown below:



Performing this cycling assignment algorithm for all OD pairs on the network will yield the number of existing cyclists expected to use a link in the network.

Note that we assume here that cyclists are equally likely to choose each of the efficient routes. To further calibrate this algorithm, a study is necessary to better understand cyclist preference when faced with a choice of routes such as the ones given above, which will be subject to further research in the future. For the time being, we assume that cyclists spread out equally along the efficient routes.

Estimating demand of a new cycling facility:
One or more new cycling facilities can be added to the network containing all current infrastructure. Existing cyclist demand is forecast based on the cycling assignment method as described above for an augmented network with additional links corresponding to new facilities. This allows us to capture not only the effect of inserting a single piece of new infrastructure into the network but also of inserting multiple adjacent (connected) pieces. One would expect to see more usage of adjacent cycle paths as they provide continuity and longer pieces of infrastructure with relatively high suitability.

Outline of new facility demand estimation algorithm:

1. *Input: cycle demand matrix, road network, list of new cycle facilities*
2. *For each new cycle facility (or several thereof), do the following:*
   2.1. *Insert new facility into the existing network, do the following:*
      2.1.1. *Run cyclist assignment for augmented network*
      2.1.2. *Derive and store existing cyclist estimate and derive new cyclist estimate for new cycle facility (facilities)*

We assume that the number of new cyclists using a facility is correlated to the number of existing cyclists – if many existing cyclists find a facility useful, it can be inferred that many new cyclists will use it. MWH Wellington and ViaStrada (2008) suggest that in New Zealand new cyclists are estimated to be 20% of the existing cyclists, whereas Krizec et al. (2007) suggest that the number of new cyclists ranges from 21% to 104% depending on their distance from the cycling facility. Utilising the more conservative estimate, we estimate the number of new cyclists as 20% of existing cyclists. The sum of existing and new cyclist demand yields the total cyclist demand for a facility.

A better way of estimating new or induced demand is to assume that the cyclist demands in the demand matrix are a function of the length of available cycling routes and their suitability for a given OD pair. From this induced demand, the number of new cyclists using a new cycling facility can be derived. Again, we aim to further investigate this in future research.

3.2 Calculating benefits and costs (Step B)

The second step in the overall portfolio selection method is to obtain the benefits and costs for each of the new facilities when built individually and combined with adjacent new facilities. Both the benefits and costs are calculated using the existing NZTA method. As described earlier the major determining factors in the computation of benefits are the demand estimates, which we obtain using the new demand forecast methodology. A crucial difference to the original procedure is that we determine BCRs for individual new facilities but also for combinations of adjacent new facilities. Hence, we determine BCRs for individual projects but also for pairs of projects. We obtain costs w_j and benefits b_j for each individual project j from which BCRs are derived. We also derive *additional* benefits b_{ij} when implementing both projects i and j in conjunction (as opposed to the sum of individual benefits $b_i + b_j$).

3.3 Selecting projects using a quadratic knapsack model (Step C)

The objective in selecting which of the n projects to implement is to maximise the sum of the individual benefits as well as the additional benefits when two projects are implemented in conjunction with each other. To select this optimal portfolio of cycling projects, the final step in the new portfolio selection method uses a Linearised Quadratic Knapsack Problem (LQKP) (Kellerer, Pferschy & Pisinger 2004) as shown below. We define the following decision variables x_j and y_{ij} as

$$x_j = \begin{cases} 1 & \text{if implementing proposed project } j \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if implementing proposed project } i \textbf{ and } j \text{ in conjunction} \\ 0 & \text{otherwise} \end{cases}$$

Parameters are b_j, the benefit of implementing proposed project j and b_{ij}, the additional benefit (or dis-benefit) of implementing proposed projects i and j in conjunction. We denote by w_j the total cost of implementing proposed project j and C is the total available budget. One constraint ensures that the sum of the costs of the implemented projects is within a given budget C, and the other constraints ensure that a joint benefit of two projects is only accounted for in the overall benefit calculation (i.e. the objective function) when both individual projects are selected. This leads to the following optimisation problem:

LQKP: Linearised Quadratic Knapsack Problem formulation.

$$\text{Maximise} \sum_{j=1}^{n} b_j x_j + \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij} y_{ij}$$

$$\text{Subject to} \sum_{j=1}^{n} w_j x_j \leq C$$

$$y_{ij} \leq x_i$$

$$y_{ij} \leq x_j$$

$$x_j, y_{ij} \in \{0,1\} \text{ for } i,j = 1 \dots n$$

LQKP is a linear integer programme and can be formulated and solved by an appropriate solver such as the open source solver COIN-OR CBC (2011). An optimal solution of LQKP will yield the projects to be implemented for a maximal overall benefit while staying within the available budget. Projects selected are those for which $x_j = 1$.

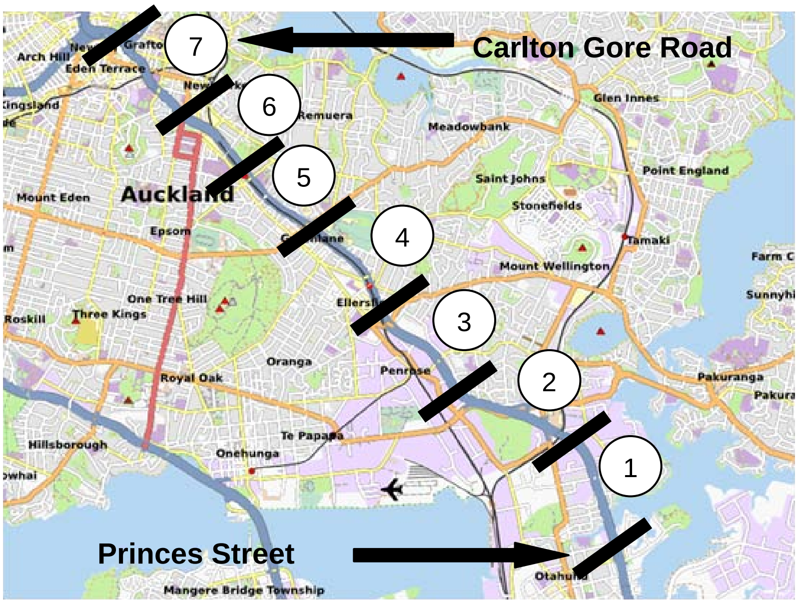
4. Case Study

In this section we demonstrate the new methodology by means of a case study.

4.1 Obtaining a list of projects

A focus area was selected to illustrate the proposed portfolio selection method for metropolitan Auckland. We choose a corridor along the Southern Motorway (SH1) which runs from Princes Street in Otahuhu to Carlton Gore Road in Newmarket (see Figure 4). The corridor is split into seven projects, in the following also denoted components, of which each represents a proposed cycling facility. The facilities are numbered 1 to 7 and their approximate location is indicated in Figure 4.

Figure 4: Case study area with seven components. Background image: OpenStreetMap (2011)



4.2 Demand forecast methodology (Step A)

Given that the focus area and the different proposed components have been selected to demonstrate the new methodology, the next step is to forecast the number of existing cyclists and the number of new cyclists which are expected to use the components individually and in conjunction with adjacent components. As described in Section 3.1 the number of existing cyclists are forecast using the cycling assignment algorithm. The Auckland road network data set that is used was extracted from OpenStreetMap (2011), which is an online collection of geographical data and maps. For the cyclist demand matrix we use a car demand matrix reduced to the current cyclist mode share by applying a corresponding factor. This is used to estimate the number of existing cyclists per new facility using the cyclist assignment algorithm. As discussed in Section 3.1 the number of new commuter cyclists are taken to be 20% of the existing cyclists, which is a more conservative estimate than the one used in the current estimation process used by NZTA (see Section 2.2).

The total facility demand forecast figures derived according to Step A in Section 3.1 are shown in Table 1. Each column shows the demand estimates for particular components added to the existing network. Columns one to seven show total demand estimates when inserting each of the components individually and columns eight to thirteen show demands when inserting combinations of two adjacent components. The last column represents the insertion of all seven components into the network.

Table 1: Total demand estimates when augmenting the existing network by new components.

	Individual components							Pairs of components						All
Comp.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**1+2**	**2+3**	**3+4**	**4+5**	**5+6**	**6+7**	**1-7**
1	59	-	-	-	-	-	-	65	-	-	-	-	-	66
2	-	124	-	-	-	-	-	128	136	-	-	-	-	163
3	-	-	138	-	-	-	-	-	157	273	-	-	-	334
4	-	-	-	157	-	-	-	-	-	218	209	-	-	294
5	-	-	-	-	185	-	-	-	-	-	312	209	-	435
6	-	-	-	-	-	355	-	-	-	-	-	448	535	702
7	-	-	-	-	-	-	767	-	-	-	-	-	833	881

Two observations can be made. Firstly, the largest cyclist flows are estimated when the entire corridor is considered (column ‘All’). Flows when components are added in conjunction with adjacent components are generally higher than flows when components are considered individually. This is because when components are considered in conjunction with others, they provide a longer continuous corridor of relatively high suitability for cycling in the network and therefore generally become more attractive for cyclists, who are more willing to take a small detour to reach a cycling facility when it is longer. This clearly shows that examining combinations of components (and thus projects) is a vital part that must be considered when forecasting demands as network effects do have an influence on cycle infrastructure usage. Secondly, as the components get closer to the central business district (increasing component numbers), the flows also progressively increase. This is to be expected as the central business district is a major destination for cyclists.

4.3 Calculating benefits and costs (Step B)

From demand forecast figures for the focus area, benefits consisting of individual benefits and the additional benefits of projects in conjunction with each other are derived. Costs of the individual components are estimated using the existing framework. The derived values for the benefits of individual projects, and the additional benefits of projects in conjunction with each other are given in Tables 2 and 3. It should be noted that all benefits have been discounted to their net present value using a period of 30 years, a demand growth rate of 4.1% and a discount rate of 8.0% (rounded to the nearest $100). Comparing benefits in Tables 2 and 3 we see that in all cases, having combinations of components yields larger total benefits over and above the benefits of individual components.

We also estimate costs for the individual projects. We assume capital and maintenance costs are linearly dependent on the length of the piece of infrastructure. When compared to path length, capital costs of components 1 and 2 are low due to the location of these paths, and components 3-6 are more expensive. Finally component 7 would involve building a cycle bridge and is therefore the most expensive component. Cost estimates are based on typical construction cost rates (as provided by NZTA). Following the existing NZTA procedure capital costs have been discounted to their net present values (NPV) using a period of 0.25 years (i.e. assuming a construction period of 3 months) and a discount rate of 8.0% per annum. The maintenance costs have been discounted to their NPV over a period of 30 years, also with a discount rate of 8.0% per annum, and assuming a cost inflation growth rate of 4.1% per annum. A summary of combined CAPEX and OPEX costs (to the nearest $100) is given in Table 2. Benefits and costs in Tables 2 and 3 are approximate estimates only.

Table 2: Final benefits and costs for individual projects in case study.

Component	Length (m)	Existing Demand	New Demand	Total Individual Benefit (NPV)	Combined CAPEX and OPEX cost (NPV)
1	2405	49	10	$617,700	$601,300
2	1976	103	21	$1,298,200	$494,000
3	974	115	23	$1,444,800	$482,400
4	2054	131	26	$1,643,700	$1,017,300
5	1465	154	31	$1,936,900	$725,600
6	985	296	59	$3,716,800	$487,800
7	1888	639	128	$8,030,300	$1,916,000

Table 3: Additional benefits for project components in conjunction with each other.

Component	Existing Demand	New Demand	Total Additional Benefit (NPV)
1+2	9	2	$115,100
2+3	26	5	$324,600
3+4	163	33	$2,052,100
4+5	149	30	$1,874,100
5+6	98	20	$1,235,400
6+7	205	41	$2,575,600

4.4 Quadratic knapsack model (Step C)

Based on the results obtained by solving the Linearised Quadratic Knapsack model for our case study using the benefits and costs listed in Tables 2 and 3 above, as well as a budget of $3,500,000, the recommended optimal portfolio of cycling paths consists of components 5, 6 and 7. It has an optimal objective value, i.e. benefit, of $17,494,900 and total cost of $3,129,400. This portfolio clearly shows how interdependencies between projects are taken into account as the projects selected form a continuous corridor. Additionally, these components are closest to the CBD and have the largest flows, which again emphasises that the demand forecast is a crucial component in the selection of a cycling portfolio.

4.5 Comparison of quadratic knapsack model and simple rank order

We have already seen that the optimal portfolio for the quadratic knapsack model consists of components 5, 6 and 7 at a total cost of $3,129,400. Let us now observe the solution that is obtained using the original simple rank order selection. Based on the benefits and costs from Section 4.3, we see that the BCR ratios for the seven components are 1.03, 2.63, 3.00, 1.62, 2.67, 7.62 and 4.20 respectively. Based on these ratios, the portfolio obtained based on a simple rank order consists of components 3, 6 and 7 at a total cost of $2,886,200.

This comparison highlights several strengths of the newly developed model. Firstly, the rank order solution selects components without consideration of connectivity as there is a large gap between components 3 and 6. This is one of the weaknesses of the model discussed in Section 2.4 that is overcome in the new model by selecting components which form a continuous corridor whenever additional connectivity benefits are high. Secondly, all components of the knapsack solution are close to the CBD where cycling demands are high.

We compute the portfolio BCR of a portfolio by computing the ratio of portfolio benefit over cost. The optimal portfolio for the knapsack model therefore has a portfolio BCR of 5.60. The portfolio BCR of the rank order portfolio is 4.57 when based on individual benefits only. It is only fair to compute the rank order portfolio's BCR including additional benefits, even though they did not influence the portfolio selection process. Hence, the portfolio BCR of the rank order portfolio calculated including the additional benefit of constructing components 6 and 7 in conjunction, yields a portfolio BCR of 5.46. This is smaller than the knapsack portfolio BCR of 5.60. This clearly illustrates that our new methodology leads to the selection of a portfolio with overall higher portfolio BCR. Thus overall, although the knapsack model's solution is more costly than the rank order solution, we believe it presents better value for money.

5. Conclusions and further work

We describe NZTA's current cycling portfolio selection method and identify potential flaws in the process. Those are the process of estimating existing demand for a facility, not taking into account network effects, and the selection of a portfolio following a simple rank order.

The new methodology provides a first step in overcoming some of the weaknesses of the existing approach. We propose a new method for the estimation of the number of cyclists expected to use a proposed cycling facility, which formally derives demand estimates for facilities that are yet to be constructed. A particular strength of this approach is that it allows us to quantify network effects of adding one or more new facilities into an existing road network. Hence it allows us to estimate resulting usage of a particular facility given its location within and connectivity to an existing road and cycle network. The proposed portfolio selection strategy selects an optimal portfolio with maximal benefit for a given budget taking network benefits (or dis-benefits) of projects into account. A novel aspect of this approach is that network connectivity becomes an important factor in obtaining an optimal portfolio. This new methodology has been partially validated by means of application to a real case study.

For road controlling authorities with budget constraints for new cycleway infrastructure, our methodology provides a project selection and prioritisation approach based on whole network benefits, rather than on an individual project basis. This may be a useful decision making aid for funders in the delivery of best value for money.

Future validation will include the derivation of more accurate cost estimates and a validation of demand forecasts. Further to the work presented here we plan to apply the developed methodology to a case study where there may be reduced benefits, for example, in the case of parallel cycling facilities. We also plan an application to a larger set of potential projects to demonstrate the feasibility of the presented approach. While estimating joint benefits of pairs of adjacent projects was appropriate for the presented case study as it formed a corridor, this may not be sufficient in general. In this case the quadratic knapsack model can be extended to include joint benefits of groups of three and more projects. Furthermore, comparing predicted to observed cyclist flow on a new piece of infrastructure that was built would help verify the validity of the approach. We would also like to further investigate how cyclists choose between different alternative routes instead of just splitting demand evenly between efficient routes. Better estimation of numbers of new cyclists (or induced demand) that start cycling as a direct result of constructing a facility is another interesting direction of research.

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References

Aultman-Hall, L.; Hall, F. & Baetz, B. (1997) Analysis of Bicycle Commuter Routes Using Geographic Information Systems -- Implications for Bicycle Planning *Transportation Research Record*, 1578, 102-110

Cherkassy, B.; Goldberg, A. & Radzik, T. (1996) Shortest path algorithms: Theory and experimental evaluation, *Mathematical Programming*, 73, 129-174

COIN-OR CBC (2011) COIN-OR MILP Solver, viewed 20 May 2011, <http://www.coin-or.org/projects/Cbc.xml>

Hartman, J.C. (2007) *Engineering Economy and the Decision-Making Process*, Prentice Hall.

Hinton, M., & Teh, C. (2008) *Auckland Region Walking and Cycling Strategy*

Kellerer, H., Pferschy, U., & Pisinger, D (2004) *Knapsack problems* Berlin: Springer-Verlag.

Krizec, K., Poindexter, G., Barnes, G. & Mogush, P. (2007) Analysing the Benefits and Costs of Bicycle Facilities via Online Guidelines Planning, *Practice & Research*, 22, 197-213

Martins, E. (1984) On a multicriteria shortest path problem *European Journal of Operational Research*, 16, 236-245

MWH Wellington & ViaStrada (2008) Estimating demand for new cycle facilities in New Zealand <http://www.nzta.govt.nz/resources/research/reports/340/index.html>

NZ Transport Agency (2009) *Planning for Walking and Cycling,* viewed 3 March 2010, <http://www.nzta.govt.nz/planning/process/walking-cycling.html>

NZ Transport Agency (2010) *Economic Evaluation Manual 2,* viewed 5 April 2010, <http://www.nzta.govt.nz/resources/economic-evaluation-manual/volume-2/index.html>

OpenStreetMap (2011) *The Free Wiki World Map,* viewed 10 August, 2011, <http://www.openstreetmap.org>

Ortúzar, J. D. & Willumsen, L. (2002) *Modelling Transport,* Wiley.

Planning for Walking and Cycling, NZ Transport Agency (2009), viewed 3 March 2010, <http://www.nzta.govt.nz/planning/process/walking-cycling.html>

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. & Ehrgott, M. (2009) *Applying Bi-objective Shortest Path Methods to Model Cycle Route-choice* ATRF 2009 Proceedings

Stinson, M. & Bhat, C. (2003) Commuter Bicylist Route Choice -- Analysis Using a Stated Preference Survey *Transportation Research Record*, 1828, 107-115

World Resources Institute (2010), viewed 2 August 2010, < http://www.wri.org>