Bi-objective Cycle Route Finding

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Abstract

Selecting a route to cycle from one point to another requires considering several often conflicting factors. We considered two objectives – the distance of a certain path and a measure of its "attractiveness", which we compiled as a linear combination of several factors. Using freely available data and bi-objective minimization techniques we developed a web application that gives users a range of different options for selecting a cycle route representing the different trade offs between as short a route as possible and as attractive a route as possible.

Key words: Bi-objective, multi-objective, shortest path, cycling.

1 Introduction

Cyclists in Auckland and throughout many cities in the world are a rarity. This is often due to safety concerns as well as a lack of information about cycle routes. High traffic volumes, irresponsible vehicle drivers and the general lack of cycle ways are some of the factors that keep cyclists off the road (Harkey, Reinfurt, and Knuiman 1998). The need for safe cycle journeys is a requirement before cycling can be promoted as a commuting alternative. Hence, Auckland City Council must identify methods that improve cycling safety if it wants to see an increase in people choosing cycling as an alternative travel option (City 2009).

This paper discusses the implementation of a cycle web application that aids users with finding suitable routes from A to B within the Auckland region. It utilizes operations research techniques to do so. This is a practical application of the bi-objective optimization algorithm. Instead of finding the shortest path several factors are taken into consideration to find multiple best routes. The cyclist can then choose the best route based on his skills and experience. Factors that define the suitability of a route such as safety have been quantified within an index. This index is based on several road features which make up for the attractiveness of a route. The bi-objective algorithm then optimizes the suitability of a route and minimizes the route distance at the same time (Raith et al. 2009). The resulting routes are not necessarily the safest or the shortest, but have a mathematically significant compromise between the index and the distance. The results are then displayed in layers on top of a map. This allows the users to easily select the route that they think is best for them.

This approach will give existing cyclists and new cyclists a larger set of information about cycling routes. The information gives them the option to improve their safety by choosing routes deemed more appropriate, even though there might be a compromise in distance. Safer route options will lead to a more cycle-friendly environment and a possible increase in the proportion of cyclists (City 2009). Further to this, information about route choices can be of value to city councils. Evaluating the attractiveness of cycle routes in different areas of a city could help identify areas that only have unattractive routes and need better cycling facilities. This information could be of value for an economic evaluation for cycle network improvements (Raith et al. 2009).

The development of the cycle route finding application for the Auckland region will be explained. Initially the quantification of road suitability will be made clear and the data sourcing necessary for the algorithm will be laid out. Further, the graphical representation of the cycle network as well as the implementation of the algorithm is described.

2 Road Attractiveness Index (RAI)

The routes cyclists choose differ from route choice drivers of private vehicles have. Commuter drivers tend to choose routes with low travel times and low vehicles operating costs. Commuter cyclists on the other hand have multiple objectives when a route is chosen (Aultmann-Hall, Hall, and Baetz 1997). The travel time and the road suitability are factors influencing the cyclist the most. In order to obtain optimal route choices with the aid of an algorithm these factors have to be quantified (Raith et al. 2009).

The travel time of a cyclist is mostly influenced by the travel distance; typically shorter distances will lead to shorter travel times. The suitability of the road however is in itself an index of multiple factors. There are multiple papers that discuss the important factors influencing cyclist road choices. The development of the bicycle compatibility index (BCI) is a method that allows quantifying the suitability of roads (Landis et al. 1997). The Level of Service (LOS) assessment is another method that helps to quantify attractiveness. Each of these methods has its advantages and disadvantages. One of the disadvantages of BCI is that low traffic volume environments as well as significant intersections are not accounted for, but under the LOS they are. Hence a mix of both these methods has been applied to find attractiveness data in this assessment (Zealand 2005). The bi-objective optimization algorithm tries to minimize the distance as well as a term defined as the “un-attractiveness” of a road. This term is in fact an inverse of the attractiveness of a road. Several factors have been identified in literature to influence the attractiveness of a road. Cyclists are concerned with safety and safer routes tend to be more attractive. Factors such as the roadway traffic volume, the total width of the outside through lane, speed limit, driveway density, type of road surface, sidewalks, number of lanes and the size of the intersection will influence cyclists choices (Harkey, Reinfurt, and Knuiman 1998). Further to this the existence of cycle ways and bus lanes that can be shared with cyclists will make for a more attractive route (Raith et al. 2009). Each of these factors is considered for a road segment and given a ranking. As an example the width of a side lane of a road is measured. 20 points are given for a width greater than 2 metres and zero points for a width of zero metres. All widths in between these distances are scaled linearly. Every road segment is analysed in this manner. Similar procedures allow obtaining points for the traffic volume and fixed amount of points are given for the existence of cycle lanes or bus lanes. Each of the factors is scaled in proportion to their importance of the overall attractiveness. A summation of these factors results in the RAI (Harkey, Reinfurt, and Knuiman 1998).

In future work a survey of cyclists and commuters wanting to become cyclists could allow identifying factors Auckland citizens find especially important in determining route choices. The studies that have been used to identify the important factors are based on US as well as Canadian cities. New Zealands perception of attractiveness might however differ due to different driver behaviours and geography.

3 Data Sourcing

A sample application has been developed for the Auckland region. Data needed to be collected to compute the attractiveness for the road segments. OpenStreetMap (OSM) had been used to obtain road information. OSM is a collaborative project to create a free editable map of the world (http://www.openstreepmap.org). Compared to other websites such as Google Maps, OSM data can be freely downloaded and used to create applications. Road segments have street names as well as additional information such as road types (primary, secondary, residential, motorway etc.). This information has been provided by contributors in a similar fashion to Wikipedia contributors. However additional information such as the traffic volume density is not provided by OSM. In order to obtain a working application this additional data had been collected in a more manual way. The Auckland City Council has provided data for traffic volumes of major roads within the Auckland region and could be used (Council 2009). Further to this Auckland City Council tools such as a high quality aerial map of Auckland (Council 2010) have helped to measure such things as road width and number of lanes of a road. These measurements however often had to be completed on a manual basis and as a result of this only the Auckland region has been considered with the Ponsonby area having the largest set of details of road information. Other areas have partly been grouped into residential, primary and secondary roads and given a respective attractiveness score. All the extracted information is then used to calculate the RAI and store it within a database for further use in the optimization algorithm.

The acquisition of data from multiple sources proved to be manually intensive and in order to obtain accurate attractiveness values for other cities a more streamlined method and easily accessible data will be required.

4 Problem Formulation

For any given section of road there are two distinct measures – the length of the section and its attractiveness. It would be possible to combine these into one objective and find a single best path through the graph, but the manner in which they are combined will vary from user to user, and even for a given user with certain preferences the combination that gives the best route may differ for different start and end points in the same network. To address these issues and keep the choice with the users themselves we used bi-objective optimization to find multiple best paths, rather than a single best path.

Consider a path P, made up of segments. Each segment in P has a length and an attractiveness. The length of path P is defined as the sum of the lengths of the segments making up the path:

$$d(P) = \sum_{i \in P} d_i$$

The attractiveness of the path made up of distinct segments is taken to be a weighted sum of the attractiveness scores for those segments in such a way that the attractiveness is interpreted as a measure per unit length of road. For a path P the attractiveness is:

$$A(P) = \frac{\sum_{i \in P} A_i \times d_i}{\sum_{i \in P} d_i}$$

In a graph G given a start and end vertex, if there are paths connecting those vertices then it is possible to find the single shortest path, or the single most attractive path. The shortest path is found to be the one with smallest $d(P)$ among all paths connecting the start and end vertices, and the most attractive path is that with maximal $A(P)$. There are, however, paths that are neither the most attractive nor the shortest but which may represent an interesting trade-off between these objectives.

If there are two paths connecting the same vertices, one is said to dominate the other if it is better in both measures. We wish to find all paths with length and attractiveness that are not dominated by any other path. Such paths are said to be efficient; there exist no other paths with both better attractiveness and length. When considering all of the potential paths from the start to end vertices the following is true:

Path P is efficient $\Leftrightarrow \nexists P\prime : (d(P\prime) < d(P) \wedge A(P\prime) > A(P))$

We used an algorithm to find all of these efficient paths given a start end end node (Raith and Ehrgott 2009). However, before it could be applied we had to make two alteration to the attractiveness objective. Firstly, the definition of attractiveness given above is unsuitable for combining. Two attractiveness scores can not be combined without knowing the components that make each up. Secondly, the algorithm we used requires a problem with two objectives to be minimised. We used a modified attractiveness with the denominator removed, and the reversed in it a way that resulted in a minimization problem

$U(P) = A_{max} - \sum_{i \in P} A_i \cdot d_i$

That is, we subtracted each attractiveness from the maximum possible attractiveness to get the unattractiveness. We were then able to use the algorithm on the following problem:

$$\text{minimize} \left\{ \sum_{i \in P} d_i \right\} \qquad \text{minimize} \left\{ A_{max} - \sum_{i \in P} A_i \cdot d_i \right\}$$

This new formulation is not equivalent to the original formulation. However, solutions to this new problem are still relevant, and unlike the original problem the new problem can be solved in a reasonable amount of time (see (Raith and Ehrgott 2009) for details of this formulation and comparison with the original formulation).

With this formulation, the algorithm and an appropriate graph representation of a road network we were able to find all such efficient paths through the road network.

5 Graph Representation

5.1 Full Graph Representation

Road networks are represented in Open Street Maps as nodes, ways and relations. Each node represents a particular location in the world on a road or path, and has a latitude and longitude, but not a height. It is possible for multiple nodes to exist in the same location (for example when a road bridge crosses a different road). Roads and footpaths are represented as ways, which are lists of nodes with accompanying information such as the road or path type.

Together these nodes and ways define a graph, with the nodes representing the vertices of the graph and each way representing a list of edges. Using the latitude and longitude we were able to calculate the distance between two nodes and therefore construct a graph with edge lengths. Though roads can be curved and these were straight-line distances the vertices were close enough together (spaced every few metres along roads) that this method was adequate.

As some of the roads in a road network are one way the network was represented as a directed graph. Therefore most road segments were represented as pairs of forward and backward edges in the graph, as most roads are not one way roads.

A route on the road network is represented as a path in this graph, with the start and end points of the route identified as the vertices in the graph with the closest latitude and longitude.

5.2 Reduced Graph Representation

As the nodes are placed very close together (in some places as close as every metre) the created graph can be very large. We found that for the Auckland road network the resulting graph contained hundreds of thousands of vertices. For our purposes this was too large, and we came up with a method for transforming the graph into a smaller graph representing the same network by collapsing certain vertices. Vertices that are suitable for removal are in a section of road and have exactly two unique neighbours, and can be removed and the edges adjacent to them combined. See Figure 1 for an example of a single vertex on a one way street being removed, and edges adjacent to it being replaced. Note that for distance, the values are simply added. For attractiveness, however, they can not be added together. Instead the RAI are both required and combined (see Section 4).

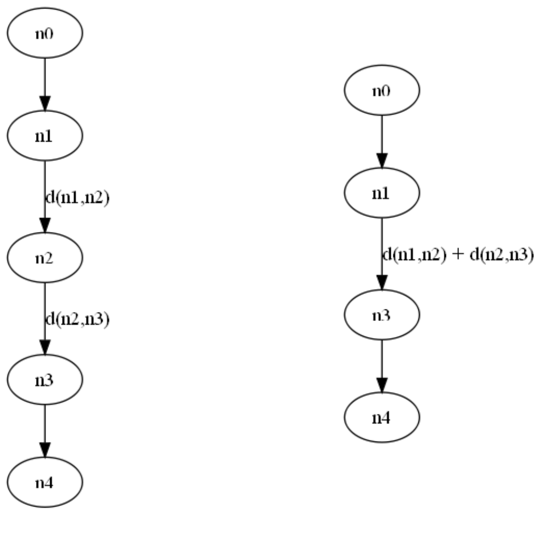

Figure 1: Collapsing a vertex and combining edges

By performing this collapsing in an iterative way all such nodes can be removed. As the removal is done edge lengths are summed. The second objective, attractiveness, is also combined in a similar way when this reduction is performed. As this measure is normalized for length, pieces are combined by calculating their average in terms of length.

Figure 2 shows a segment of road network. All the smaller nodes are candidates for removal, and after those nodes are removed and the edges combined the only nodes left will be the ones marked as larger circles.

The full graph and the reduced graph are homeomorphic; the full graph is a subdivision of the reduced graph.

Finding a path in the full graph is done as follows:

- Find the closest vertices to the start and end points (in terms of latitude and longitude) in the full graph;
- search from these vertices along edges to the closest vertices that appear in the reduced graph;
- find a path through the reduced graph connecting these identified vertices;
- unpack the removed vertices from the edges to obtain the equivalent path in the full graph;
- add the vertices searched along from the original start and end vertices.

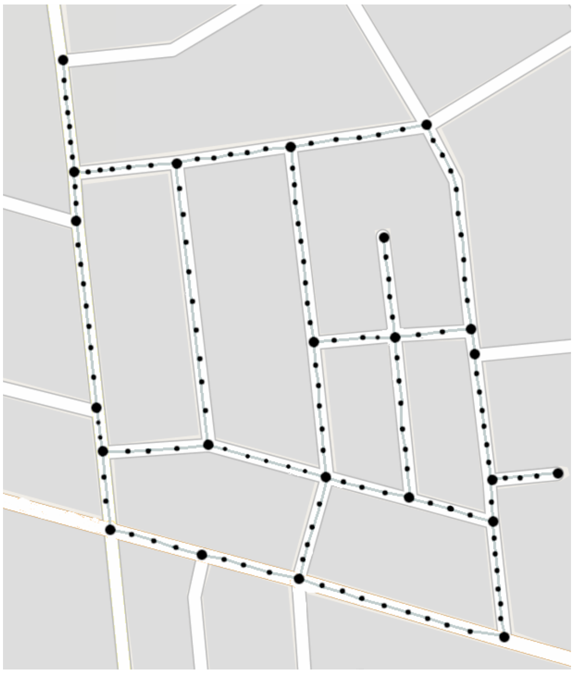

Figure 2: Only those vertices with larger circles remain after reduction

This means that a path can be found in the reduced graph (which has an order of magnitude fewer vertices than the full graph), and the full path can be reconstructed. The path in the full graph is necessary to fully describe the path geographically, but the path in the reduced graph is sufficient to uniquely identify the path.

6 Application

With the algorithm and a method of creating a graph from Open Street Maps data and calculating the distance and attractiveness scores, we were able to find all efficient paths given a start and end location. As a practical application we created a web application using the entire Auckland road network. The application has an interface similar to Google Maps, allowing zooming and panning. Users indicate the beginning and end of their journey and several potential paths are overlayed on the map. There is a small delay between the user requesting the routes and the results being displayed, but it is not significant when compared with other similar route finding websites such as Google Maps.

A problem we identified with this large network was that there are a very large number of efficient paths when the start and end vertices are far apart. If they are close to each together there may be between one and ten efficient paths, depending in the location, but when they are at opposite ends of the city there may be hundreds of efficient paths. Presenting this many paths to a user is unreasonable, as there is too much information to present in an accessible way.

6.1 Limiting The Number Of Paths

When the number of paths found is small, the web application returns and displays them all. However when it is more than a certain number (which is customizable) the number of displayed paths is limited.

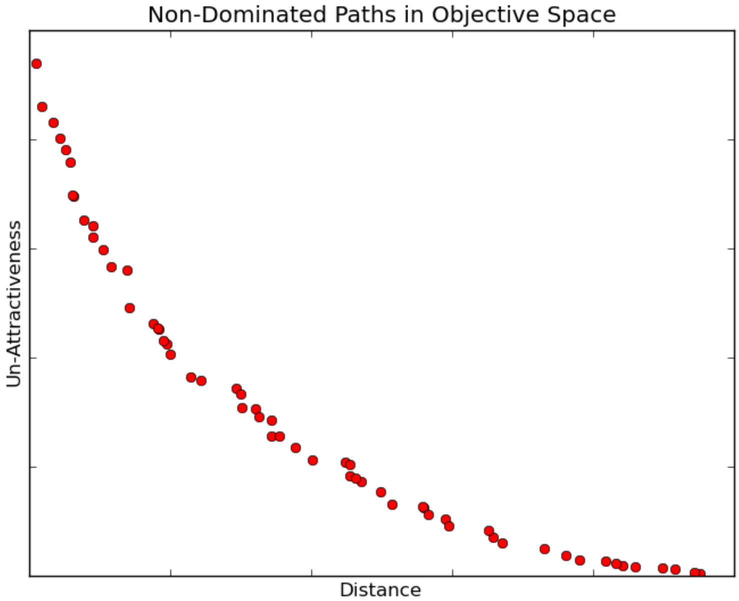

Figure 3: Example of the Range of paths found in a large network.

Figure 3 shows an example of the range of solutions returned when the start and end vertices are far away. We observed that in most cases there were two or three distinct major routes, each with many variations. For example, a major route may consist of a series of segments such that for each segment there are two choices of road to take. If there are n segments then there are 2^n different variations on the route. It is unlikely that they are *all* efficient (though it is possible), but in some cases many of them are efficient. Ideally our application would select just one or two different paths for each of these major routes and present those to the users.

The method we used to do this was select a subset of the efficient paths based on their objective functions, so that the returned paths are evenly spaced in objective space. In some cases this works well; all of the variations on one major route are very short but unattractive, all of the variations on another are long but attractive etc.

However, in other cases these variations on major routes can result in significantly different objectives (an example is a straight main road and a parallel winding minor road; the straight road is short but unattractive, while the parallel road is long but more attractive). As we did not have a precise definition of what a good subset of paths would be, we used the method described above involving objectives to select some of the paths. In practice it gave results that were adequate, but more research could be done in this area.

7 Future Work

There are a lot of expansions and improvements possible to the current version of the application. A number of points that can be considered in future versions of the application are described here.

7.1 Geographical Height Data

New Zealand and especially Auckland terrain has a lot of hills. Most commuting cyclists would prefer to take a route that does not contain any steep roads. Further, routes that are shorter in distance, but contain unnecessary hill crossings are undesirable by cyclists. Hence, a trade off between height differences and route distances is required to find the optimal route.

The current version of the application does not take heights into consideration. If appropriate data were available this function could be integrated into the model and be part of the definition of attractiveness. Hence the bi-objective optimization model would take into consideration the slope of roads when choosing routes and would provide users with more appropriate route choices.

7.2 Spatially Different Paths

As described above in Section 6.1 a different method of selecting a subset of the paths to display to the user could be investigated. Ideally the routes displayed would be spatially different to provide the user with a good range of choices. It may be possible to select these from the potential routes returned, or it may be necessary to approach the problem in a different manner and search the graph for spatially graphs directly.

Alternatively or additionally ways of displaying more of the information to the user may be investigated. Of the hundreds of efficient paths found currently only a few are used. Potentially the user could select one of the few routes returned and be given more routes that are spatially similar to that one but different in objective, allowing them to explore the solution space and refine the available options.

7.3 Automating Data Collection

As described above in Section 3 a more streamlined data collection method would be desirable. Currently public data is only available sparsely. Easily accessible data would allow automating the data collection and attractiveness calculation procedures. Some public data is available at City Councils. However if this data is not in electronic formats or is hard to access, voluntary data collection may be required. Methods similar to those used by Open Street Maps that rely on entirely voluntary data collection could be used to obtain relevant cycling data.

7.4 City Council Information

Expansions to the current application can be of great benefit to city councils. The application can be used to gather cycle information useful for cycle network improvements. As an example the application could store a history of the most desirable routes chosen by cyclists as well as the volume of cyclists using these routes. This information can then be used by city councils to make decision about future expansions of the cycle network in Auckland. This method will be a cost efficient indicator of favourable cycle routes. The attractiveness data could also indicate which city areas would need more improvements in order to create more attractive route choices.

8 Conclusion

Cycling is an activity councils such as the Auckland City Council try to promote as an alternative and sustainable method of transportation. However safety concerns and a lack of information about safe routes are often reasons commuters opt not to cycle. Hence, city councils try to find methods to improve safety or inform cyclist about safe routes that are available.

In this report, a practical application of the bi-objective optimization algorithm has been presented in the development of a web application that allows cyclists to find suitable routes from A to B. By using both the distance as well as a set of road information called attractiveness the cyclist is given multiple route choices. Each of them provides a compromise between distance and attractiveness and allows cyclists to make the best cycle decision from the choice of routes available.

The web application is easily accessible and has a user interface similar to Google Maps. Expansions of the application to include geographical data and a better choice of spatially different paths would allow the algorithm to show more relevant optimal routes. Further, possibilities to work with city councils could give access to better sets of data and the inclusion of application tasks that will gather useful information for councils will allow for improvements to the actual cycle networks.

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