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Designing a route planner to facilitate and promote cycling in Metro Vancouver, Canada

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A B S T R A C T

With increasing fuel costs, greater awareness of greenhouse gas emissions and increasing obesity levels, cycling is promoted as a health promoting and sustainable transport mode. We developed a cycling route planner (http://cyclevancouver.ubc.ca) for Metro Vancouver, British Columbia, Canada, to facilitate cycling amongst the general public and to facilitate new route location by transportation planners. The geographical information system-based planner incorporates variables that influence choices to travel by bicycle (e.g., distance, elevation gain, safety, route features, air pollution and links to transit) in selecting the preferred routing. Using a familiar and user-friendly Google Maps interface, the planner allows individuals to seek optimized cycling routes throughout the region based on their own preferences. In addition to the incorporation of multiple user preferences in route selection, the planner is unique amongst cycling route planners in its use of topology to minimize data storage redundancy, its reliance on node/vertex index tables to increase efficiency of the route selection process, and the use of web services and asynchronous technologies for quick data delivery. Use of this tool can help promote bicycle travel as a form of active transportation and help lower greenhouse gas carbon dioxide (CO_2) and air pollutant emissions by reducing car trips.

1. Introduction

In contrast to driving, cycling is one of the most sustainable forms of transport (Gatersleben and Appleton, 2007). Cycling offers benefits to both individual and environmental health, and is one way to help address several major societal issues: climate change, increasing obesity levels, and depleted oil reserves (Wen and Rissel, 2008; Maibach et al., 2009). Using a bicycle for transportation incorporates physical activity into daily routines, and can also help reduce automobile congestion and traffic-related air and noise pollution (Cavill and Davis, 2007). Cycling is relatively fast over short distances, and it provides a reliable and affordable form of transport for most segments of the population (Lumsdon and Tolley, 2001). Sælensminde (2004) estimated that the benefits (health, reduced noise and air pollution) of investments in cycling infrastructure are 4–5 times greater than the costs and concluded that such investments are more beneficial to society than automobile-related transport investments. In North America, a very small proportion of the population commutes by bicycle (Gatersleben and Appleton, 2007). Cycling mode share is 1.2% for work trips in Canada, compared to 10–30% for some European centers (for example 20% in Denmark and 32% in the Netherlands) (Pucher and Buehler, 2006). Cycling promotion

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efforts now need to reach the next wave of cyclists – ‘‘contemplators” (Prochaska, 1994) – those who might be willing to start, given the right circumstances.

The much higher levels of cycling in Europe are believed to stem from urban transport policy shifts in the 1970s to curb car travel and promote transit, walking, and cycling as the socially and environmentally friendly travel mode (European Conference of the Ministers of Transport, 2003, 2004). Cycling infrastructure in Europe is more extensive than in North America and is much better integrated with public transit, thus facilitating travel by bicycle. Hochmair (2005) suggests that cyclists would use bicycles for more trips if they had trip information ahead of time. This possibility was also evident from the Cycling in Cities survey recently completed in Metro Vancouver. In this survey, a population-based sample of 1402 current and potential adult cyclists were asked about 73 factors that might influence their likelihood of cycling, a list derived from extensive review of the scientific and grey literature and expert input on cycling motivators and deterrents (Winters et al., 2010). The web-based or mail survey queried how each of the factors influence their decision to cycle with five response options, ranging from ‘‘much less likely to cycle” to ‘‘much more likely to cycle”. Of the list, two information-related factors: ‘‘a web-based route planning tool is available” and ‘‘information about cycling routes to the destination is available” were ranked in the top 15 motivating factors, and were similarly important to different types of cyclists, including regular commuters and occasional cyclists.

2. Cycling route planners

The findings of the Cycling in Cities survey and the growing number of general online route planners (e.g., Google Maps, Google Transit, Microsoft Live Search, MapQuest and Yahoo Maps) suggest an increasing demand for spatial decision tools for everyday transport. Desktop computer mapping and routing software (i.e., software installed and running on a computer without internet interactivity, for example, network analysis in ArcGIS) has intensive rich media applications with instant responsiveness that, until recently, was difficult to achieve with internet approaches (Garrett, 2005). With the latest advancement in asynchronous technologies such as Asynchronous Javascript eXtensible Markup Language (AJAX) increased functionality can be provided online. Rich media applications such as Google Maps and Google Transit enable the general public to go beyond static location information queries to interactively find optimal routes between locations.

Existing online route planners primarily designed for cycling purposes allow for manual route selection from a set of predefined routes (EMS, 2005), for adding stops between start and end of the predefined route (Ehlers et al., 2002), for arbitrary selection of start and end notes (MAGWIEN, 2009), as well as routes that avoid steep slopes (Bikemetro, 2009), or those that are fast, scenic and short (Rad.RoutenPLaner, 2003). These route planners provide only very limited functionality in terms of their decision rules, that is they either have a single attribute optimization function (e.g., shortest path), or (rarely) use a compensatory decision rule involving user-defined criteria (e.g., short and scenic route) with importance weights. Non-compensatory techniques using eliminatory constraints (such as whether only bike lanes should be used) are even less frequently found in existing systems (Hochmair and Rinner, 2005). With Google Maps' rich media information (e.g., street maps, satellite images, street level photos, and neighborhood facilities), highly responsive AJAX technologies, and user-friendly interface design, some online bicycle trip planners embedded its content into their own websites. Examples include the byCycle trip planner (http://byCycle.org for Milwaukee, WI and Portland, OR, accessed November 23, 2009, referred to as byCylce) and the San Francisco bike route planner (http://amarpai.com/bikemap/bikemap.html for San Francisco, CA, accessed 23.11.09, referred to as SF Cycle). However, online trip planners rarely provide the complete set of route-selection criteria required for a bicycle trip planner including fast, safe, simple and attractive routes (Hochmair, 2005).

While examples such as byCycle and SF Cycle provide some non-compensatory options (such as ‘‘normal” and ‘‘safer” routes from byCycle and ‘‘most bike-friendly”, ‘‘balanced” and ‘‘shortest path” from SF Cycle) they provide few compensatory options under a non-compensatory criterion. For example, a cyclist choosing the route with the most bike facilities might simultaneously prefer a route having the most vegetation cover or the lowest pollution. Further, the existing cycling trip planners do not provide sufficient context information for route selection alternatives. If a user lacks information about possible consequences of his/her selection, the results of a decision on preferences may be unexpected and frustrating due to an incorrect user model (Hochmair and Rinner, 2005).

2.1. Cyclevancouver

To respond to a reported need from the local population and a desire amongst the wider cycling community (see http://www.petitiononline.com/bikether/petition.html, accessed 23.11.09) for additional route planners, we developed a bicycle route planner for Metro Vancouver, ‘‘Cyclevancouver”, combining the best practices in designing a bicycle route planner (Hochmair, 2005), and incorporating key routing preferences identified in the Cycling in Cities survey (Winters et al., 2010). This tool was developed to facilitate bicycle route planning for the general public, as well as to aid transportation planners in the optimization of cycling networks. As described in the following sections, this route planner includes both non-compensatory selection criteria (such as whether only bike lanes should be used), and compensatory environmental options (such as most vegetation cover and least traffic-related air pollution). In addition to the incorporation of multiple user preferences in route selection, the planner is unique amongst cycling route planners in its use of topology to minimize data storage redundancy, its reliance on node/vertex index tables to increase efficiency of the optimal route selection process and its use of web services and asynchronous technologies to create a rich media application with quick data delivery. To our knowledge, this is the first documented cycling route planner using Google Maps mashup techniques and integrating both compensatory and non-compensatory criteria.

3. System design

In this section we describe the design of the cycling route planner, especially its computation of routes based on identified cycling route-selection criteria. Unique elements of the user interface are described and we provide some general comparisons to other online route planners. We then describe the actual algorithm for routing computation and outline the interaction between server and client for asynchronous responses.

3.1. User interface design

The user of a route planner should have the ability to choose between a range of route-selection criteria; however, the number of offered criteria from which the user can select must not be too large to overwhelm human cognitive capacities in information processing (Miller, 1956; Rosch, 1978). We developed route selection preference options based on the Cycling in Cities survey of Metro Vancouver cyclists, and following prior research and existing route planners (Hochmair, 2005). From the local Cycling in Cities survey, the most influential criteria on decisions to travel by bicycle (based on mean influence scores) were related to: pollution (#1 factor – "route away from traffic noise and air pollution" – 96% of respondents responded they would be likely or much more likely to cycle); aesthetics or greenspace (#2 – "route has beautiful scenery" – 90%); bicycle routes (#3 – "paths separated from traffic" – 86%); topography (#4 – "route is flat" – 84%); and distance (#6 – "less than 5 km" – 75%) (Winters et al., 2010). In a survey of cycling route-selection criteria, Hochmair (2005) identified "bike lanes" as the most important from amongst 35 criteria (mentioned by 78% of the participants), followed by "short", "sights", "avoid heavy traffic", "parks" and "avoid steep street segments". As with byCycle and SF Cycle, we also allowed users to choose routes including designated bicycle routes, a combination of bike routes and other road categories, or any road type.

Unlike the familiar Google Maps "driving or walk there" and Google Transit's "take transit there" functionality, we also allowed users to select compensatory options (Hochmair and Rinner, 2005) (e.g., least elevation gain), as described in more detail below. Further, to provide additional context to facilitate a user's ultimate route choice, our planner not only suggests routes with street by street turns, distance of each street and total distance traveled (as in SF Cycle and byCycle), but also estimates time spent (according to a user specified travel speed), greenhouse gas (i.e., carbon dioxide – CO_2) emissions prevented (compared to vehicle travel), total calories burned, the mean air pollution level (based on nitrogen dioxide as a marker of traffic-related air pollution), total elevation gain and mean vegetation cover. Options are also provided to output computed routes as printer-friendly files, as .kml files for visualization in Google Earth, as well as coordinates for upload

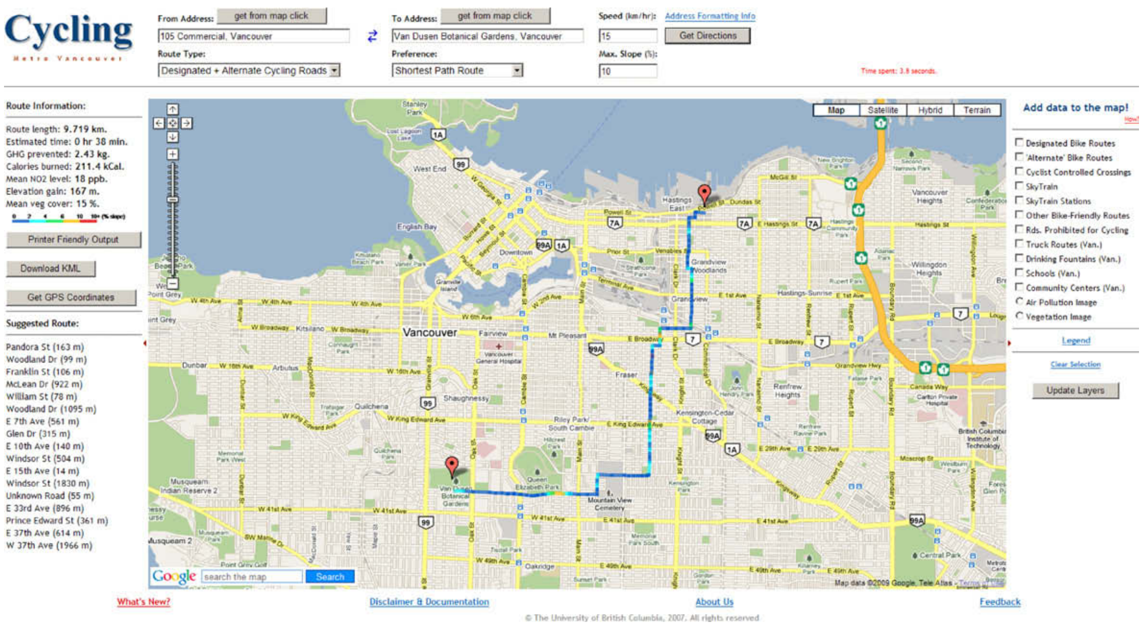

Fig. 1. Screenshot of cycling trip planner output, including route map and detailed route information.

to a GPS device. The design of the interface (Fig. 1) and its functionality (http://cyclevancouver.ubc.ca) follow the principle of fast, safe, simple and attractive as specified by Hochmair and Rinner (2005).

The next sections outline key elements of the trip planner, including origin and destination selection, route preference criteria, contextual information, and estimation of route parameters.

3.1.1. Selection of origin and destination

The system is designed to find optimized routes between origins and destinations in the Metro Vancouver region. Either specific addresses, intersection information (e.g., Broadway and Clark), or names of popular places can be entered, or alternatively, locations can be selected via interactive point-and-click identification on the map (Fig. 1). Google Maps' geocoding services convert user entries into latitude and longitude coordinates. A Structured Query Language (SQL) is used to find the network nodes nearest to the user's origin and destination in the underlying cycling network database.

3.1.2. Topography preference options

Interviews with bicyclists and transportation design guidelines indicate that reasonable road grades for cycling are less than 10%; on steeper slopes, walking is preferred (Transportation Association of Canada, 1999; Ardigò et al., 2003). We therefore included a maximum slope gradient as a default constraint of the route selection with a threshold of 10% (Fig. 1). The slope gradient of street segment AB is defined as the rise over the run as in

$$m = \Delta y / \Delta x \tag{1}$$

where Δx is the horizontal distance of street segment AB, and Δy the elevation difference between street intersections A and B. When traveling from intersection A to B, $\Delta y = E_B - E_A$ and from B to A, $\Delta y = E_A - E_B$, where E_A and E_B are the elevations at intersection A and B, respectively. Slope gradient is therefore positive when going uphill and negative when downhill. Elevations of all intersections were calculated from a 30 m resolution digital elevation model (DEM) provided by DMTI Spatial (Markham, Ontario). In order to help users visually identify steep route segments, the slope gradient is also identified along the computed route using color classifications ranging from <2% to >10% (Fig. 1).

In addition to calculating slope gradients for individual route segments, we also allowed users to choose the minimum total elevation gained (M in meters) over an entire cycling route as defined in

$$M = \sum_{i=1}^{n} (\Delta y_i) \quad \Delta y_i \text{ set to 0 when } \Delta y_i < 0 \tag{2}$$

where Δy_i is the elevation difference of the ith road segment as defined in Eq. (1) and n is the total number of road segments of a chosen trip.

3.1.3. Least air pollution preference option

In Vancouver, traffic-related pollution is the main source of ambient nitrogen oxides (NO_X) (Metro Vancouver, 2005) and nitrogen dioxide (NO_2) is a marker of traffic-related air pollution (Su et al., 2009; Henderson et al., 2007). A high resolution map of annual average NO_2 concentrations for 2003 was used to provide an indication of traffic-related air pollution levels within the region. The map is based upon a land use regression model described in detail elsewhere (Henderson et al., 2007) in which air quality measurements are linked to geographic features including land use, traffic and topography. In our trip planning tool, an optimal route algorithm is used to select the route with the lowest mean NO_2 concentration for the entire route, using NO_2 concentrations as an impedance cost for the cycling network (see Section 3.2).

3.1.4. Most vegetated preference option

Landsat Enhanced Thematic Mapper Plus (ETM+) data from the United States Geological Survey (USGS) for 2001 were used in a Classification and Regression Tree (CART) model to classify land cover types for the region into seven classes (Su et al., 2008). CART is a nonparametric statistical procedure that identifies mutually exclusive and exhaustive subgroups (Breiman et al., 1984) and produces visual output that is a multilevel structure resembling branches of a tree. Land cover classified as trees, park, forest and grassland was used to calculate the green cover along each street, based on the percentage of area within 50 m of the road segment that was vegetated. In the trip planning tool, an optimal route algorithm is used to select the route with the highest mean green cover for the entire route length, using this as an impedance cost for the cycling network (see Section 3.2).

3.1.5. Route type options

With the cycling route planner, a user also has the option of selecting a preference for the type of cycling infrastructure. The cycling network includes officially designated routes as well as "alternate" routes. Designated routes are city-specified, and include specific amenities for the convenience and safety of cyclists (e.g., signage, road stencils and traffic circles) according to design guidelines (Transportation Association of Canada, 1999). Alternate routes are suggested by cyclists and municipal planners as cycling-friendly routes, but may lack comprehensive cycling amenities and are not officially designated by the regional transportation authority (Translink). The cycling network data were obtained from Translink, municipal data, and periodic cycling network field validation studies. The complete road network, based on route logistics data from DMTI Spatial (Markham, Ontario) was used to allow no restriction options to cycling route types.

3.1.6. Additional trip planning features

While the planning tool computes optimal routes based on preferences, a user can also visualize the entire cycling network on the Google Maps interface. In addition, cyclist activated traffic signals, transit stations and bus stops, roads prohibited to cyclists, truck routes, public drinking fountains, schools, community centers, parks, and maps of air pollution levels and vegetation cover can also be visualized alone or in combination with computed routes to facilitate trip planning. This additional contextual information is helpful in determining preference for compensatory route-selection criteria and in reducing a user's demand for eliminatory constraint functionality (Hochmair and Rinner, 2005).

3.1.7. Estimation of prevented CO_2 emissions and calories burned

Though cycling increases the exhalation of CO_2 because of increased physical activity, this increase is minimal compared to the CO_2 emitted by a car traveling the same distance. As such, we calculated the CO_2 emission "savings" from cycling by estimating emissions for the same distance if traveled by a motor vehicle. A typical late-model sport utility vehicle driven 20,000 km a year produces about 6 tonnes of carbon dioxide, compared to 4 tonnes for a recent mid-sized sedan, and 2 tonnes for a gasoline-electric hybrid vehicle (Natural Resources Canada Office of Energy Efficiency, 2005). Based on the composition of the passenger vehicle fleet in Canada, we estimated 5 tonnes of CO_2 emissions from an annual travel distance of 20,000 km for a typical passenger car, equivalent to 0.25 kg km^{-1} travelled. The estimated direct CO_2 emissions prevented (kg) during a bicycle trip are therefore equal to the distance traveled in kilometer multiplied by 0.25 kg km^{-1}.

Lowe (1988) estimated that on average a person uses 35 cal when traveling on a bicycle for a mile. The calories burned during a bicycle trip are estimated as the distance traveled in km multiplied by 21.75 cal km^{-1} (the metric equivalent).

3.2. Optimal route selection algorithm

Given the need to incorporate multiple user-defined preferences and route-selection criteria described above, the route planner also required an efficient route selection algorithm. One of the oldest and most widely used approaches in network optimization is shortest path analysis (SPA) (Dijkstra, 1959; Dantzig, 1960; Floyd, 1962). The objective of SPA is to find a path between origin and destination such that the sum of the weights (impedance costs) of its segments is minimized. In our application, we were interested in searching for the shortest path with cost impedances for attributes based on the user-defined preferences for one of two route networks – cycling routes only or including all roads, and amongst four preferences: total elevation gain, restricted maximum slope gradient, traffic-related air pollution and vegetation. Many optimization problems are solved using a matrix of dimension $n * n$ (e.g., Dijkstra, 1959) by various constraints such as the inclusion of specific nodes or a specific number of nodes (Deo and Pang, 1984), or nodes within a pre-specified covering distance of every node in the network (Current et al., 1984, 1994). These algorithms usually search more neighboring nodes or roads than those physically adjacent to the node of interest.

An alternative to SPA that saves processing time is the use of topology. Since networks usually have a topological structure that identifies how the various features relate to one another (e.g., position, orientation, adjacency and connectivity), the topological relationship of nodes and roads can be stored efficiently in an index table and loaded into memory when a client launches a rich media web application. Further, using topological structures significantly increases the efficiency of finding an optimal route by only looking at the physical neighbors of a node based on adjacency and connectivity. In simple terms, the topology-based optimal route algorithm first identifies the starting road intersection (node) of a trip and *marks* it. All physically adjacent streets (links or edges) and corresponding road intersections that a cyclist can travel to (see below from Eq. (3)) from this identified road intersection are then *tracked* (but not marked), their impedances calculated separately and added to corresponding total impedances. The road intersection of the least total impedance to the original starting road intersection among all the *tracked* road intersections is identified and *marked*, and used as a new starting road intersection to find its physically adjacent and travelable streets and road intersections. This process continues until the latest start road intersection meets the destination road intersection (i.e., a route is found) or until the two never merge after assessing all the travelable road intersections (no direct route). The following section describes details of the optimal route selection algorithm.

3.2.1. Algorithm details

The topology of the cycling network is modeled using its environmental weight (based on the selection of route preference) as a directed graph $G = (V, E)$ in the two dimensional plane, where $V = \{v_1, v_2, \ldots, v_n\}$ is the set of nodes in the network and $E = \{e_1, e_2, \ldots, e_n\}$ is the set of directional links/edges connecting nodes. These environmental weights, described in the previous sections, are: elevation gain for the "least elevation gain" preference, % vegetation cover for the "most vegetated route" preference, average pollution for the "least polluted route" preference, distance for the "shortest path route" preference and slope for the "restricted maximum slope" preference. Because cyclists are restricted to the same directional laws as motorists, a link is asymmetric on one-way streets and symmetric on two-way streets. The physical neighbor set of node v_i is defined as in Eq. (3).

$$NS^i = \begin{array}{ll} \{v_k|(v_i, v_k) \in E(G) \text{ or } (v_k, v_i) \in E(G)\} & \text{with two way connections} \\ \{v_k|(v_i, v_k) \in E(G) \text{ and } (v_k, v_i) \notin E(G)\} & \text{with one way connection from } i \text{ to } k \\ \{v_k|(v_i, v_k) \notin E(G)\} & \text{with no direct access (wrong way)} \end{array} \quad (3)$$

where node v_k is the physical neighborhood of node v_i via link/edge e_i. NS^i is the number of physical neighborhoods of node v_i. For two way links, travel from node v_k to v_i and from node v_i to v_k via link e_i are both allowed. For one way links, only travel from node v_i to v_k is allowed, but routing opposite the direction of travel (v_k–v_i) is prohibited. Each directional link has four environmental weights (i.e., impedance costs or weights) from node v_i to v_k, also called $w(i, k)$, although only a single weight is applied for a trip dependent upon the user-selected preference (i.e., least elevation gain, most vegetated route, least polluted route, shortest distance path, or restricted maximum slope). Environmental weights are used to represent the cost associated with an individual street and route weights to represent the sum of all environmental weights of a path. Therefore, the minimum weight route is defined as the path with the least route weight of a preference among all the routes connecting two network nodes of origin and destination. It is also important to note that $w(i, k)$ and $w(k, i)$ are different environmental weights based upon the direction of travel. For example, if moving uphill from node v_i to v_k, elevation gain $w(i, k)$ is greater than 0; by contrast, it is downhill from node v_k to v_i and $w(k, i)$ is 0. If a street is one way and runs only from v_k to v_i, the environmental weight $w(i, k)$ was not used when seeking physical neighbors of node v_i.

3.2.2. Algorithm examples

The structure of topology used to calculate a minimum route weight is illustrated in Fig. 2 which also describes examples of the algorithm. Each node v_i contains its physical neighbor nodes $v_j \in NS^i$ ($j = 1, 2, \ldots, m$), corresponding environmental weights, the number of physical neighbor nodes, and the starting location of the node v_i in the node index table. Two sorting functions are implemented, with the left side topology sorted by the FROM nodes and right side by the TO nodes in an ascending order. Sorting by FROM nodes is used to compute the minimum weight route, and sorting by TO nodes to trace the nodes from the destination of a selected route to its start address for final display of connecting streets. When a client launches the cycling route planner, the topological structure is read into memory during the web page loading process to reduce web response time during the route selection process.

Specifically, to search for a minimum weight route the following algorithm is applied (for examples, refer to Fig. 2):

(1) A vector (V) of length n (n = total number of nodes) is identified with node ID. Each node ID is also associated with a binary value of indicating that it is marked or unmarked (initially all unmarked), the cumulative route weight to it from the origin v_0 (initial value = *null*) and, if marked, its FROM node ID (for tracing back the final optimal route). A collection S (initially empty) is designed to store the nodes with the minimum route weight to v_0. Starting from v_0, the route weights of the physical neighbors of v_0 are calculated based on the topology. The environmental weights vary from v_0 to v_j and $v_j \in NS^o$ (Eq. (3)).

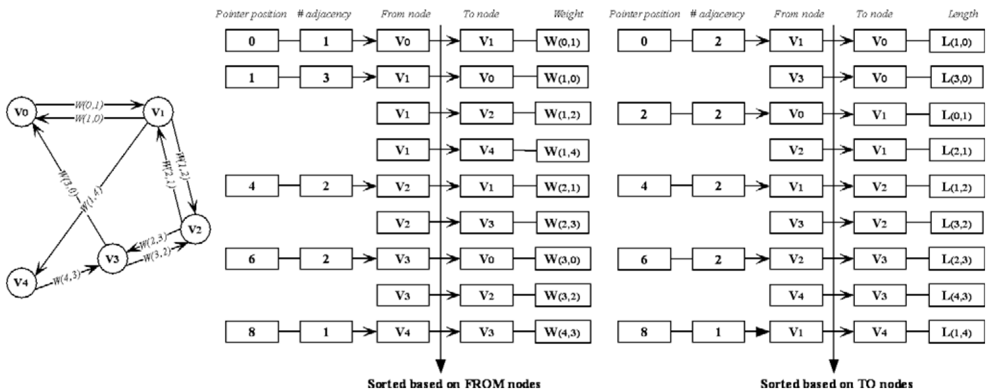

Fig. 2. The topological structure for selection of an optimal route (sorted using FROM nodes) and back tracing the nodes on the chosen optimal route (sorted using the TO nodes). If a route starts from v_4 (i.e., v_0) and ends at v_1 (i.e., v_d), the defined topology sorted by FROM nodes guides the pointer to move directly to position 8 on the index table (no loop from position 0 to 8). Since there is only one physical neighbor node (v_3) for the origin, the environmental weight $w(4, 3)$ is identified as the minimum weight from origin v_4. The pointer then identifies that node v_3 starts from position 6 on the index table and the pointer is moved to that position. As there are two physical neighbor nodes identified by the # adjacency attribute, the pointer loops through the two neighbors (v_0 and v_2), and updates their cumulative route weights. Node v_3 is then marked and added to collection S. As node v_0 and v_2 are the only two unmarked nodes of all the non-null cumulative route weights, the minimum route weight of these two nodes is used to update the cumulative route weights of its physical neighbor nodes. For example, assume node v_2 has the minimum route weight. Because v_2 has only one unmarked physical node: node v_1, the cumulative route weight to v_1 is updated. Because v_1 is the destination point, the search stops even though v_0 is not marked. If neither v_0 nor v_1 is the destination, then all the unmarked nodes including v_0 and v_1 are compared and the smallest cumulative weight is used to update the cumulative route weights of the node's physical neighbors before being marked and added to collection S. Because most of the street intersections have 1–4 road links, there is no need to sort a environmental weight.

(2) An unmarked node v_i with the least cumulative environmental weight $W[i]$ of all the unmarked routes is selected using Eq. (4):

$$W[i] = Min\{W[l]v_l \in V - S\} \tag{4}$$

where S is the collection of the marked nodes and V the total number of nodes of a road network. v_l and $W[l]$ are the lth node of the unmarked nodes and corresponding cumulative weight. *Min* is a function to find the least cumulative weight.

(3) Based on the topological structure, a loop function is implemented to update the cumulative route weights of the physical neighbors of node v_i. v_i is then marked and added to collection S as defined in Eq. (5).

$$S = S \cup \{v_i\} \tag{5}$$

If the destination node v_d is not marked and the cumulative route weights to the unmarked nodes are not *null*, step (2) and (3) are repeated until the algorithm finds node v_d (optimal route) or the number of repetitions equal to the number of nodes but v_d is still unmarked (no direct route).

3.3. Asynchronous response system

The another unique feature of the route planner is the application of an asynchronous system to hasten the delivery of route selection data. In a traditional synchronous web application (Fig. 3a) a user triggers a Hypertext Transfer Protocol (HTTP) request to a web server. The server then processes the request and returns a HyperText Markup Language (HTML)

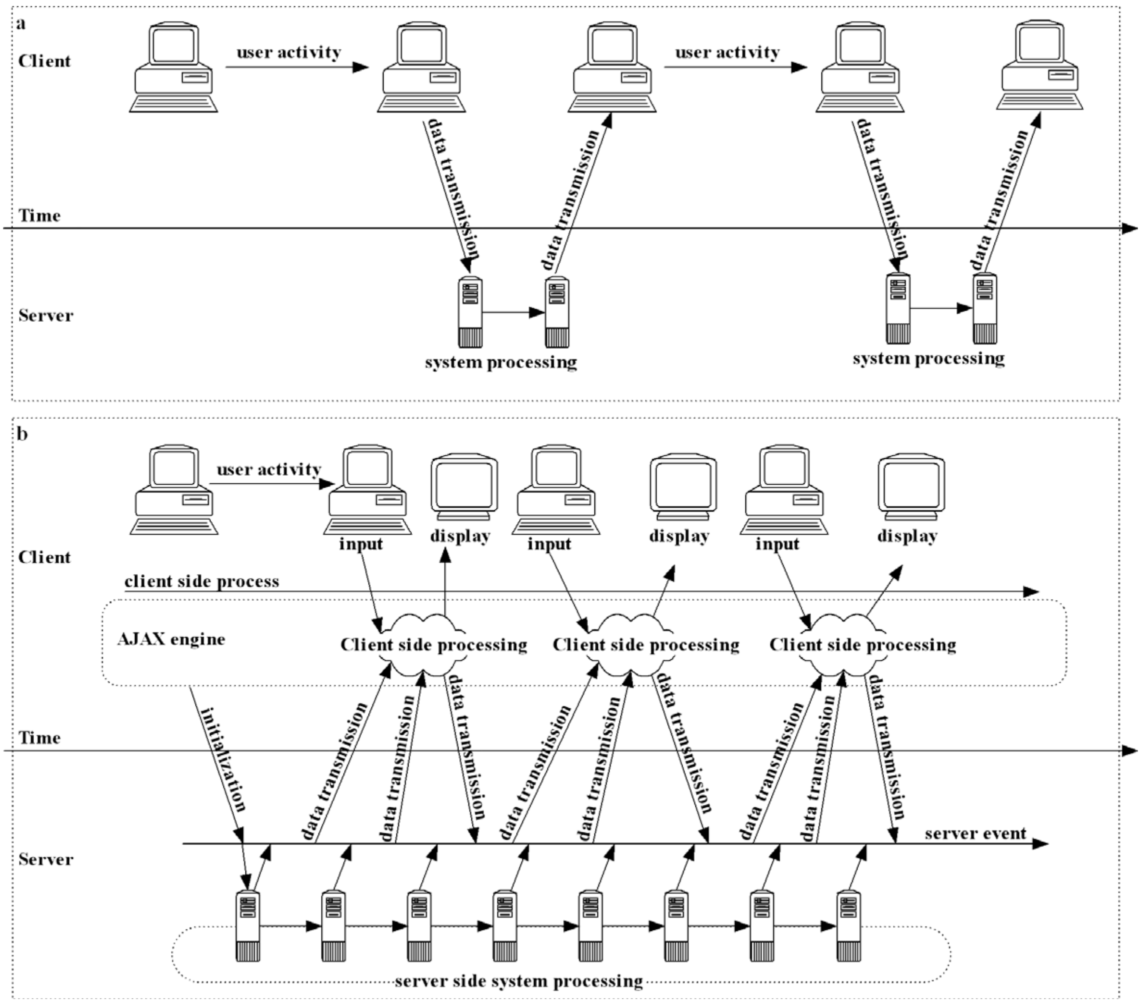

Fig. 3. Typical synchronous web application (a) and the asynchronous response system of trip planner (b). Fig. 3 is modified from Garrett (2005).

page and/or images to the client. After a user initializes a request, the interaction with the web stops. In contrast, the asynchronous system in the route planner (Fig. 3b) can deliver data to the client at any time, as opposed to only in response to user input. This substantially reduces the data delivery delay. The detailed asynchronous responses in the route planner are as follows:

(1) When the route planner is launched an AJAX command requests the loading of Google Maps content (e.g., regional street map and satellite images) from Google onto the planner. This request does not trigger any server side event on the route planner server. Simultaneously a second message is sent to the route planner server for attributes and geocoded locations (e.g., cyclist activated signals). A third message is also sent during the page loading process to establish connections with the cycling network database and read the data and related topology into the server's memory. Because all these steps are requested asynchronously during the webpage initialization and loading process, there is minimal time delay and no user input is required.
(2) A second series of asynchronous responses are triggered when the user requests a selected route by clicking the "Get Directions" button (after typing start and destination addresses or clicking these locations on the map). The origin and destination addresses are sent using AJAX to Google Maps for geocoding. The two geocoded locations then trigger an asynchronous response from Google Maps to resize the map appropriately for the chosen locations. Additionally, this triggers the bicycle activated and bus stop signals to be displayed on the client computer. The geocoded origin and destination street addresses are also sent to the route planner server to identify the two nearest network nodes of origin and destination. Next, the two network nodes are used to estimate an optimal route based on the user's specific route-selection criteria. As the cycling network topology and related data are already loaded into memory during the page initialization and loading process, no further interaction with the server is required. This reduces the burden on the server and each session only requires a few seconds of connection to the server database and acquisition of necessary data (during the initialization and loading process).
(3) At this stage, the optimal route selection algorithm relies on data stored in server memory to estimate an ideal route according to the user's selected preferences. The optimized route is linked to the slope gradient data and each street segment is color-coded accordingly when displayed on the user interface. Street by street directions, route length, estimated trip time, CO_2 emissions avoided, elevation gain, calories burned, mean NO_2 concentrations and vegetation cover on a chosen trip are calculated and displayed below the "route information" or "suggested route" title on the interface. Options are also provided to download the computed route text directions and map for printing, .kml files for visualization in Google Earth or other geospatial programs, and as coordinates for uploading to GPS devices.

4. Case study

To demonstrate how the route planner can meet cyclist-specific needs, example routes are described below. For simplicity we assume that all cyclists choose routes that include a mix of cycling routes and major roads during their trips and applied a cycling speed of 15 km h^{-1}. Another option not demonstrated here is the selection of only the city-designated and alternate cycling routes. All the scenarios are for a trip that starts at a local park in a residential area, and ends at the University of British Columbia.

Assume cyclist A_1 has entered a preference for a route that restricts the maximum slope gradient to 10%. The route planner outputs street-by-street directions in text, a map of the suggested route (A_1 in Fig. 4) color-coded according to the slope gradient, and calculated "route information" (A_1 in Table 1). This optimized route would take about 49 min to cycle and have no streets segments with a slope gradient greater than 10%. On this trip A_1 would avoid 3.1 kg of CO_2 emissions, and burn 268 cal (A_1 in Table 1). However, A_1 will experience a slope gradient 6–10% along the northwest portion of the route.

In another situation, cyclist A_2 wants to further restrict the maximum slope gradient to 6%. The route planner output for A_2 is listed in Table 1 and the suggested route displayed on A_2 in Fig. 4. The differences between A_1 and A_2 show that A_2 will be guided through a more southerly route than A_1 to avoid steep slopes to the north. The maximum slope gradient on A_2's trip is 4%.

Assume cyclist B selects the preference for a "least polluted route" to avoid exacerbating asthma. The planner will guide B primarily through the green park/forest area with its low levels of traffic-related air pollution.

In another scenario cyclist C selects the "least total elevation gain" option. C will be guided on a route with longer total distance than the least polluted route, but with less net elevation gain (C in Fig. 4). Though the suggested route has the least total elevation gain, C could also find that they would experience less vegetation cover during this trip (mean vegetation cover 30%) compared to others (Table 1).

Similarly, assume cyclist D selects the "highest vegetation cover" option. While cycling on the west side of the route, D's trip is similar to B's; however, part of the route instead follows major arterial road bordered by green space. This demonstrates that the highest vegetation cover does not necessarily guarantee the least polluted road, though such differences might be small (B vs. D in Table 1).

Finally, assume cyclist E selects the "shortest path" option. The route output follows mainly local roads and is the shortest (10.6 km) of any of the routes.

In addition to using the route selection algorithm, a user can also check if a street segment is a designated or alternate bicycle route or on a major road by displaying the appropriate layers in the user interface. Further, users can also locate

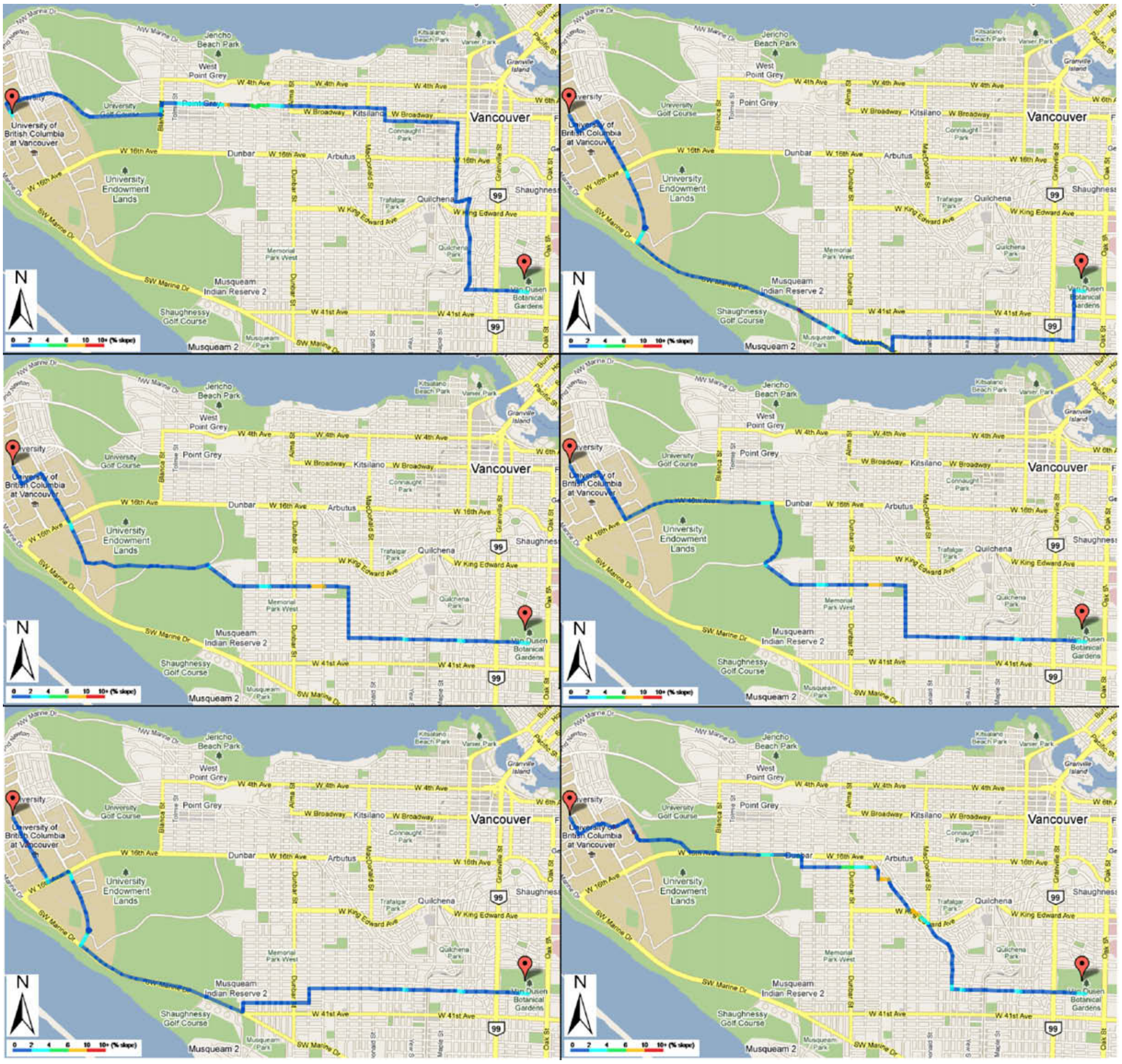

Fig. 4. Cycling trip planner case study results of six scenarios based on users' preferences. All the scenarios assume the strip starts from Van Duesen Botanical Gardens and ends in Environmental Health Sciences, the University of British Columbia (2206 East Mall, Vancouver).

Table 1
Route planner output and responsiveness for case study, based on user-selected routing preferences.

	Route preference[a]					
	A_1	A_2	B	C	D	E
Route length (km)	12.3	11.7	10.6	11.4	10.9	10.6
Estimated time (min)	49	46	42	45	43	42
CO_2 prevented (kg)	3.1	2.9	2.7	2.9	2.7	2.6
Calories burned (cal)	268	255	231	248	237	230
Mean NO_2 concentration (ppb)	16	15	14	14	14	14
Total elevation gain (m)	116	113	109	91	110	139
Mean vegetation cover (%)	30	35	33	30	35	26
System responsiveness based on ISDN testing:						
Route calculation time (s)	3.9	3.7	3.8	4.8	3.5	3.9

ISDN: Integrated Services Digital Network.
[a] A_1 and A_2: restricted maximum slope gradient is 10% and 5%, respectively; B: least traffic pollution route; C: least total elevation gain route; D: most vegetated route, and E: shortest path route.

connections with the public transit system (therefore facilitating multi-modal transportation), search for locations of destinations (using Google to search the map) and even find where the location of public drinking water fountains along cycling trips. In conducting the case study, the average system time spent in finding an optimal route and calculating GIS output using an internet connection of speed 100 kbps was approximately 3.9 s, roughly 5 times faster than the byCycle route planner. The result for each scenario is summarized in Table 1.

5. Summary and conclusions

We developed a web-based cycling route planner (http://cyclevancouver.ubc.ca) that assists cyclists and would-be cyclists in finding routes that fit their personal preferences. Using the popular and user-friendly Google Maps interface, the planner allows individuals to choose routes throughout Metro Vancouver based on user-stated preferences regarding safety, distance, elevation gain, air quality, and areas featuring trees and other vegetation. Users can choose trips that follow city-designated and alternate cycle routes only, or trips that include major roads. This cycling route planner calculates the number of calories burned over the course of a given route, and also estimates the savings in CO_2 emissions, compared to the same trip taken by car. A user can visualize designated, alternate and other cycling-friendly routes on the route planner interface. Other features such as cyclist controlled traffic crossings, transit locations, roads where cycling is prohibited, and maps of pollution levels and vegetation cover are also available for assistance in route planning.

At present, there is no scientific literature on cycling route planning applications using Google Maps' mashup techniques. Though the use of Google Maps for driving and walking, or Google Transit for public transportation has become extremely popular, there are only very limited Google Maps mashup applications available for cycling, and the applications that currently exist are only for the shortest path routes or a small set of non-compensatory selection criteria (such as whether a route includes only bike). Even the recent introduction of a cycling option in Google Maps for many large U.S. cities, only incorporates cycling route and elevation (hills) in its route planning. The Metro Vancouver cycling route planner, by contrast, provides both non-compensatory (i.e., the selection of a route type) and compensatory functions (e.g., least total elevation gain, least polluted route and most vegetated route). The design of the planner follows fast, safe, simple and attractive principles as specified by Hochmair and Rinner (2005).

One of the unique aspects of the route planner is the optimal route selection algorithm. Compared to the traditional shortest path algorithms, our methodology, which relies on topological structure to conduct route search and on asynchronous techniques for server initialization and data preloading, significantly reduces the time required for data delivery to users. Because AJAX is implemented from web initialization to the final output display, the route planner is highly responsive. For example, while the Metro Vancouver cycling and major road network has 19,000 street intersections, 66,000 vertices and 22,500 streets/off-street bike lanes the route planner uses only 3–4 s on average to find an optimal route and calculate outputs on a computer with a connection speed of 100 kbps.

Given the interest in supporting cycling as a form of active and environmentally friendly transportation, this planner is a useful tool for both experienced and new cyclists as it allows for preference options in routing. The popularity of Google Maps as a motor vehicle route planner suggests cycling route planners with this familiar interface will also be widely adopted, thus addressing key goals of addressing cyclist comfort and safety, and increasing bicycle mode share. Future enhancements such as Google Street View visualization of selected routes would allow cyclists to virtually experience a suggested route before actually taking the trip, an option now possible by exporting a route file to Google Earth.

As suggested by Hochmair (2005) and the Cycling in Cities survey (Winters et al., 2010), people will be more likely to cycle where there are connected bike routes, less motor vehicles, fewer hills and aesthetically pleasing environmental conditions such as more greenery, less pollution and less noise. Based on feedback from cyclists and policy makers who use the route planning tool, municipal and regional transportation planners can identify disconnected routes systematically and make corresponding amendments to improve cycling networks. By overlaying pollution data, the vegetation data, and the cycling network on the route planner, policy makers can identify priority neighborhoods and places for the development of cycling routes. Quick visual inspection of color-coded slope gradients along routes allows planners to identify sections of the cycling network where route options with lower slope gradients should be identified. Overall, the route planner can assist planners to optimally design cycling networks online before implementation.

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