DATA REQUIREMENTS AND GRAPH DATA STRUCTURES FOR A MULTI-MODAL, MULTI-OBJECTIVE TRIP PLANNER

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ABSTRACT

Traffic congestion has a significant impact on the economy and environment. Encouraging the use of multimodal transport (public transport, bicycle, park’n’ride, etc.) has been identified by traffic operators as a good strategy to tackle congestion issues and its detrimental environmental impacts. A multi-modal and multi-objective trip planner provides users with various multi-modal options optimised on objectives that they prefer (cheapest, fastest, safest, etc) and has a potential to reduce congestion on both a temporal and spatial scale.

The computation of multi-modal and multi-objective trips is a complicated mathematical problem, as it must integrate and utilize a diverse range of large data sets, including both road network information and public transport schedules, as well as optimising for a number of competing objectives, where fully optimising for one objective, such as travel time, can adversely affect other objectives, such as cost. The relationship between these objectives can also be quite subjective, as their priorities will vary from user to user.

This paper will first outline the various data requirements and formats that are needed for the multi-modal multi-objective trip planner to operate, including static information about the physical infrastructure within Brisbane as well as real-time and historical data to predict traffic flow on the road network and the status of public transport. It will then present information on the graph data structures representing the road and public transport networks within Brisbane that are used in the trip planner to calculate optimal routes. This will allow for an investigation into the various shortest path algorithms that have been researched over the last few decades, and provide a foundation for the construction of the Multi-modal Multi-objective Trip Planner by the development of innovative new algorithms that can operate the large diverse data sets and competing objectives.

INTRODUCTION

Traffic congestion is an important emerging issue, both here in Australia, and overseas. It has adverse effects on both the economy and the environment, due to time lost and the extra emissions produced by vehicles while they are travelling. One method of combating congestion is to provide the traveller with real-time information so they can decide how they get to their destination in terms of mode of travel, time for departure and the path travelled. This paper will outline the data requirements and data structures required for a multi-modal multi-objective trip planner that will be able to provide users with this information.

This paper will have the following format: First, a review of some of the trip planners available around the world will be presented. Next, the various sources of data that will be used by the trip planner will be outlined, and categorised into two groups: mandatory data that is required in order for a basic trip planner to function, and useful but optional data that can provide extra functionality to the trip planner. Information will then be presented on the graph data structures representing the road and public transport networks, which will be used in the trip planner to calculate optimal routes. Finally, a discussion on how these data requirements and structures will be used in the implementation of the trip planner will be presented.
REVIEW OF CURRENT TRIP PLANNERS WORLD-WIDE

There are many trip planners that have been implemented to service certain areas around the world, with a diverse range of features. This section will compare several of them, summarising what features they provide, to show what is commonly available as well as features that are not as common.

The trip planners that are being reviewed below include the following:

c) TriMet (US) - http://trimet.org/
d) Goroo (US) - http://www.goroo.com/goroo/showTripPlanForm.htm
e) Mapquest (US) - http://www.mapquest.com/
g) DB Bhan (Germany) - http://reiseauskunft.bahn.de/bin/query.exe/
h) My Journey (UK) - http://www.connectteesvalley.com/jplanner1.asp

These trip planners have a number of common features, as well as features that are less common and only implemented by a few of them. These features include:

- Multiple options for transport mode for trip
  - Automobile
  - Walking
  - Bicycle
  - Bus
  - Train
  - Ferry
  - Plane
- Multiple options of objectives for optimisation of the trip
  - Quickest journey
  - Cheapest journey
  - Most environmentally friendly
  - Shortest walking distance
  - Limited number of transfers
  - Minimum elevation change for walking or cycling
- Choice of input of departure time or arrival time
- Multiple input options for start and destination locations
  - Textbox input
    - Station or Stop
    - Address
    - Point of Interest
- Map input
- Output information for journey
  - Route information
    - Text display
    - Map Display
  - Number of Transfers
  - Expected travel time for each trip in journey
  - Travel Distance for automobile
  - Travel Distance for walking/cycling
  - Departure Time or estimated time of arrival
  - Cost Information (Fare for public transport, Petrol/Parking costs for automobile)
  - Expected waiting times for public transport
  - Elevation graph for walking or cycling
- Real-time Information
- Traffic conditions and delay information
- Weather Information
- Ticket booking facility
- Accessible by mobile applications

Table 1 summarises which of these features are available in each of the reviewed trip planners, to give an indication of which features are common or not.

All of these trip planners provide at least one type of public transport in their mode options, however only half of them also calculated automobile trips, and three of them included travel by air. From the five trip planners that calculated automobile trips, only two of them, Goroo and DB Bhan allowed for multi-modal trips that included both automobiles and public transport. Bicycle routes were only provided by four of the ten trip planners.

The entire set of trip planners calculated the quickest trips as a default search, however optimising for other objectives was not as common as an available feature. The next common objective that was available was for the minimisation of number of transfers with six of them providing it, followed by shortest walking distance with four trip planners accounting for it. Only three trip planners provided for cost as an objective, and only one trip planner, Transport Direct, optimise for most environmentally friendly. None of these trip planners optimised for minimum elevation change for walking or cycling. The difference in the number of objectives that are available is most likely due to the availability of other sources of data such as fuel costs, fares, elevation data and carbon footprint for the trip planner’s region.

All of the trip planners computed shortest paths for departure time and arrival time inputs, therefore this should be considered a mandatory feature in the trip planner. All of the trip planners provided text boxes for input of origin and destination locations, although they varied in what types of locations they allowed to be input. Most, but not all, allowed for saving locations for future use. Also, only half of the trip planners allowed for locations to be input via a map, and the implementation of how they are input varies between these trip planners.
Table 1: Features of Trip Planners from around the world

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*Columns are as follows: (a) Translink; (b) Transperth; (c) TriMet; (d) Goroo; (e) Mapquest; (f) Rutebok.no; (g) DB Bhan; (h) My Journey; (i) Transport Direct; (j) Hyperdia. Links to these trip planner websites are shown at the start of this section.

**--(dash)** represents not applicable (N/A), for Travel Distance for Automobile, as several of the trip planners do not provide automobile routes.
Most of the trip planners used real-time data in one way or another, mainly for their public transport timetables, although none of them use this data in the calculation of an optimal journey. Many of them also provided incident information on their homepage and delay information, although only one of them, My Journey, provided maps with congestion levels on it. Weather Information and Ticket Booking facilities were not a common feature, with two trip planners implementing each of these features. This is most likely due to the fact that these features would be provided by a third-party outside of the trip-planner website. All but one of the trip planners provided some method of accessing the information via a mobile device, which is could and should be considered mandatory due to the nature of planning and taking a journey.

DATA REQUIREMENTS

The most important component of the multi-modal, multi-objective trip planner is the data from which it can compute trips for users. There are a number of different data sources that will be used by the multi-modal trip planner, and can be categorised into two groups, mandatory data that will be required for the basic functions of the trip planner, and optional data that would be useful in order to provide extra functionality to the trip planner.

Mandatory Data

In order to perform the basic functions of a multi-modal trip planner, there are several sources of data that need to be obtained, both from the end-user of the trip planner, as well as from back-end databases. This section will outline these data sources, including the specific details of data formats and what functions they will provide to the trip planner.

The end-user must input several pieces of information in order to produce a basic trip plan that caters to their needs. These include:

- The source destination, i.e. where they are starting their trip. This can be provided in 3 different ways; longitude and latitude coordinates (which could be obtained from a GPS device or by using an interactive map within the UI), or by providing a street address or landmark name, which can then be looked up in a database to find their coordinates.
- The destination location, i.e. where they would like to end their trip. This data is obtained in a similar fashion to the source destination, by either directly providing longitude and latitude coordinates or by providing an address or landmark name.
- The choice or choices of transport mode for the trip. The user can choose one or more of the following modes of transport: Private Automobile, Bus, Train, Ferry, Bicycle or Walking. The trip planner will then use these choices to plan alternative optimised routes, either by a solo mode of transport or by combining a number of modes.
- The time of departure or time of arrival. The user must choose to enter one of these times, depending on whether they need to arrive at a destination at a certain time, or leave from their current location at a certain time.
- Average walking speed and maximum walking distance, if applicable. In order to calculate the time taken to travel by foot during a journey, the average walking speed needs to be provided by the user. This can either be input as a specific velocity value or chosen from a number of preset choice values (slow, medium or fast). The maximum distance the user is willing to walk in one leg of the trip needs to be provided as well.
- Bicycle riding speed and maximum distance travelled by bicycle, if applicable. For the same reasons as the average walking speed and maximum walking distance, these parameters must be provided by the user in order to calculate appropriate trips for them.

Once the information described above has been obtained from the user, the trip planner requires access to a number of data sources from back-end databases in order to accurately calculate and efficiently optimise a trip for the user. These include:
• A method or database for finding a location given a street address, otherwise known as geocoding. This is necessary to calculate the “last mile” of the journey, both from the origin and the destination, where the user will only travel a certain distance along a certain link in the network.

• The road network as a graph data structure. This consists of two groups of data that relate to each other, Intersection data and Road data. Intersection details include longitude and latitude coordinates, as well as any turning restrictions that are applicable, such as no right-turn or a permitted u-turn. Road attributes include the name or description of the road, the IDs of the start and end intersections for the road (which can be used to indicate direction), the length of the road and the free-flow speed or speed limit on the road, which can then be used to calculate the travel time along the road. Alternatively, real-time or historical data can be used to provide a time-dependent travel time along the road link. Other attributes that could be provided for the road but are not mandatory include the type of road (highway, arterial, suburban, etc) which can be used for safety purposes, and the number of lanes.

• The public transport network as a graph data structure. This data is more complicated than the road network, and consists of a number of related groups of information. Firstly, the physical locations and descriptions of all the bus stops, train stations and ferry terminals in the service area are required, so they can be integrated with other modes of transport by a transfer trip. Information about the routes is also required, including descriptions and the stops that the public transport visits along each route, and finally schedule information to provide estimated times that the public transport will visit each stop along the route.

• Park’n’ride locations. In order to implement a multi-modal trip planner that provides integrated trips involving both public transport and private vehicles, the locations of dedicated parking facilities are required.

• Bicycle and walking related data, including networks for dedicated tracks and additional information on the road network indicating where it is safe to walk or cycle alongside the roads.

**Useful Data**

This section will outline the useful information that would be required in order to implement extra features to the multi-modal trip planner, such as alternative objectives.

The end-user must provide their preferences for the extra features through choices made on the user interface. These may include the following:

• The maximum number of transfers between modes that they wish to make.

• The priority objective that they would like their journey to be optimised for. These objectives include:
  o Quickest journey
  o Cheapest journey
  o Safest journey
  o Least number of transfers
  o No transfers (Single mode journey)
  o Most environmentally friendly journey
  o Shortest walking distance

• Whether they would like a return trip to be included in the optimisation of their journey. Additional information will need to be provided, such as the time of arrival or departure for the return journey. This feature is particularly important for multi-modal trips where a user drives their car for the first leg of the journey, the return journey must take into account the location where the car has been parked so that the public transport leg of the journey will return them to that location.
In order to provide results based on the user specified preferences, other sources of data are needed for these extra features. They include the following:

- Cost information related to the various modes of transport. For public transport, this would include zone and fare information. The costs for automobiles include fuel costs and consumption per kilometre, car park locations and cost, and toll information. Other costs associated with automobiles such as registration and insurance fees and maintenance costs are important; however, it is difficult to include them in a trip-specific cost. Specific to Brisbane, although applicable to other cities that have similar schemes, the costs for hiring bicycles through Citycycle are also required.
- The environmental impact of the various modes of transport, in particular, the emissions produced along a journey.
- Classification of routes in terms of their safety for different modes of transport, mainly for walking and bicycles. For example, the links in the road network could include an attribute that contains a safety classification, such as low traffic suburban street = safe, arterial road = less safe, highway = restricted/no access, etc.
- Elevation information, for use on walking and bicycle trips. This could be used an option to optimise the journey, in order to calculate the least tiring journey. It could also be used as a visualisation of elevation change along the journey.
- Temporary obstruction information. This could include information on road work or track work, traffic accidents or flooding, as well as any other possible obstructions to traffic. Data that would need to be included are the roads or railway sections that are obstructed, the extent of the obstruction (1 lane, 1 side of a road or the entire width of the road, etc), and the estimated duration of the obstruction.

**GRAPH DATA STRUCTURES**

The graph data structure is an important component of a multi-modal, multi-objective trip planner. It must provide efficient access and traversal of the large data sets that are provided for use within the trip planner to allow for the quick calculation of routes, while providing as much detail as possible to ensure the routes are optimal and accurate.

There are two main data sets that need to be stored within a graph data structure for the trip planner, the road network and the public transport network, which includes stops, routes and service timetables. The approaches to representing these networks in graph data structures will be outlined in the following section.

**Road network**

The standard method of representing the road network in graph form is as follows: Intersections are represented by node elements and roads are represented by arcs that are connected to these nodes. The arc contains information about the “cost” of traversing it, such as distance and estimated travel time, as well as other important attributes. This representation can be extended to walking and cycling paths that connect to the road network. Figure 1 illustrates the basic road network and its components.

The arcs can be either undirected or directed; however, in order to account for one-way streets, undirected arcs require an additional attribute indicating which direction is legal on that road; whereas two separate arcs are used to indicate two-way streets when using directed arcs. Figure 2 illustrates these different approaches when dealing with one-way and two-way streets.
This standard representation has difficulties in representing legal u-turns, no-left-turns and no-right-turns as well as turning delays, which are found on a real road network. There are two methods of dealing with these extra conditions. An alternative graph network has been suggested [1-3] where the midpoint of each road is represented by arcs connecting these nodes. Any turning delays are added to the travel time along the half-roads between each midpoint as the final arc cost. Alternatively, extra attributes could be added to the nodes in the standard graph data structure to indicate legal and illegal turns between arcs that connect to the node as well as any turning delays [4]. Figure 3 compares these two different representations.
Public Transport Network

The public transport network is different in structure to the road network, as it must deal with temporal components within the data structure to indicate waiting and transfer times as well as the travelling time of services between stops. There are two approaches that have been reported in literature that deal with representing the public transport network: The Time-Expanded Approach (TEA) [5-10] and the Time-Dependent Approach (TDA) [7, 9-12]. Figure 4 illustrates these two approaches and the difference between them.

![Figure 4: (a) Time-Expanded Approach (TEA); (b) Time-Dependent Approach (TDA)](Schulz 2005 p20)

The TEA involves constructing a graph where each node corresponds to a specific event in time (an arrival or departure) at a stop, and the arcs between the nodes can represent two types of activities: travel between two consecutive stops by a specific service or waiting at the stop between two consecutive services. The TDA, on the other hand, avoids maintaining a node for every single event, and instead each node represents a stop, and two nodes are connected by an arc if a route visits them consecutively. The cost attributed with the arc is calculated “on-the-fly” and is dependent on the time that will be used by a shortest path algorithm to answer a query.

The main disadvantage to the TEA is that it will generate a large graph with many nodes, dependent on the number of events that occur at each stop within the public transport network, and therefore will require a proportionally larger amount of computer memory to store the graph information. This graph will be relatively sparse, however, with two incoming and one outgoing arc for arrival event nodes, and one incoming and two outgoing arc for departure event nodes. Another disadvantage is the greater difficulty in maintaining each node in terms of processing time if a timetable needs to be altered, however this may not have a large affect on the computation time of calculating shortest paths, depending on how often the timetable needs to be updated. The main advantage of the TEA is that the graph is in a form that can be easily traversed by standard shortest path algorithms without much alteration to their code.

The main advantage to the TDA is that it does not require as much memory as the TEA, because the graph that is generated is considerably smaller, with the number of nodes dependent on the number of stops in the public transport network. The main disadvantage to the TDA, however, is the time required to calculate the cost of arcs “on-the-fly” as opposed to the TEA, where costs are calculated when the graph is first generated. This computational time depends on the type of timetable that is used by the public transport network. If services operate at regular intervals between stops, this calculation can be fairly simple and the TDA would be preferred over the TEA. However, if the services operate at irregular intervals, a search algorithm would be required to find the appropriate time and corresponding arc cost at
each node, and this computational time will add up over the course of visiting nodes during a shortest path algorithm.

The graphs in figure 4 can be extended to represent more realistic situations, such as minimum transfer times and timetables for specific days of the week [7], as well as limiting the number of transfers between services.

In a realistic situation, a minimum transfer time should be accounted for when transferring between services, to allow for deviation from the set timetable as well as travel time between stops in close proximity. The method of including this situation into the graph structure depends on the approach that is used. In the TEA, this requires the addition of some extra nodes and arcs to the graph structure, as shown in figure 5. These extra nodes are called transfer nodes, and are copies of each departure and arrival node at each stop. The arrival nodes now have two outgoing arcs, one connected to the departure node for the same service at the stop, and one connected to the next transfer node with a time value that is greater than or equal to the time of the arrival node plus the minimum transfer time. For the TDA, the minimum transfer time must be taken into account when calculating the cost of arcs that require a transfer between services.

![Figure 5: (a) simple time-expanded graph; (b) time-expanded graph with arrival, transfer and departure nodes (Schulz 2005 p39)](image)

In a realistic public transport network, some services do not operate to identical timetables every day. For instance, some services may only operate during peak hours on weekdays to cope with the extra demand, compared to the weekend. When the TEA is used, this is handled by either fully expanding the graph for each specific day of the week, or by adding extra data to nodes in the graph indicating on which days this event takes place. Fully expanding the graph for specific days greatly increase the amount of memory required to store the information and would prove infeasible and unnecessary. The addition of extra data to nodes to indicate the days they take place on would require a small alteration to the path-finding code that is used to traverse the graph, in order to ignore connections that leave a node to another stop if it is not valid for a specific day. As with the minimum transfer time, the TDA must take into account the days that a service operates when calculating arc costs.

For the problem where a limit on the number of transfers is specified, both approaches can deal with the issue in a simple manner. It involves tracking an extra variable on the arcs during the path searching algorithm, where traversing arcs that indicate a transfer between services increments the variable by one. Once the limit has been reached, the search algorithm can just ignore any further transfer arcs. Figure 6 illustrates this method for the TEA.
Integration of the Road Network and Public Transport Network

The integration of the road network and the public transport network for use in a multi-modal trip planner is a significant issue due to the differences in what nodes and arcs represent in each of their graph data structures. There are two approaches that have been researched in order to combine these networks together to calculate a multi-modal journey.

The first approach is to combine the two graphs into a multi-layered graph structure, where the two networks are on separate layers. A layer between these two contain nodes that represent methods of transfer between the two modes, such as park’n’ride areas, and the arcs connecting these nodes to the two transport networks represents costs of walking or driving between the transfer area and the corresponding network. The search algorithm that is used to calculate shortest paths can then traverse these extra arcs to go between the two different networks. This will require alterations in the shortest path algorithm code in order to deal with these extra nodes, due to the conceptual differences between their structures.

The second approach is to keep the two networks separate, and to produce multimodal trips via a multi-step algorithm. The first step is to find the stops (for walking) or park’n’ride (for automobile) within a specified distance of the origin, as well as stops within a specified distance of the destination. Then optimal paths are calculated between the origin and its corresponding stops/park’n’ride areas, taking into account the times that the user would arrive at each stop or park’n’ride. This time is then used as the departure time to calculate public transport journeys from these origin stops to the stops surrounding the destination, including any transfers between public transport modes that are required. Finally, optimal walking journeys are calculated from the departure stops to the final destination. For return journeys, this is performed in reverse.

The main difficulty for the multi-layered network approach when compared to the multi-step algorithm approach would be in the design and implementation of the search algorithm that will be used to generate shortest paths through the multi-layered graph, since additional code will be required to deal with the extra components that connect the two networks together. On the other hand, however, it may produce a single journey solution in less computational time than the multi-step algorithm approach, as the latter must find calculate several routes in each of the steps before proceeding to the next step. If a number of alternative routes need to be presented, however, the difference in the overall computational time between the two approaches should be much smaller.
CONCLUSION

This paper has investigated and presented several issues that have been encountered in the initial development of a multi-modal, multi-objective trip planner.

Firstly, a review of 10 trip planners selected from around the world has been presented, and were compared with each other in terms of the features that they provide. This comparison was performed in order to identify the gaps that are currently present in available trip planners. These gaps include the fact that the majority of trip planners are limited to the use of static information in the generation of their journeys as opposed to real-time information, as well the fact that most do not combine automobile with public transport in a multi-modal journey. Also, the choice of objectives is usually limited to minimisation of travel time and the number of transfers, whereas a user may prefer a different objective to optimise their trip for, such as cost or safety. Finally, the trip planners that do include multi-modal trips involving both public transport and automobiles do not consider the overall journey, which includes the return trip using park'n'ride into their optimisations.

The different sources of data that are needed for the implementation and operation of a multi-modal, multi-objective trip planner are then outlined. They were categorised into two groups, mandatory data that is required for a basic trip planner to operate and useful data that would be needed to additional features to be available to the user, such as alternative objectives. There are certain difficulties involved in obtaining all of this information, particularly in the useful data categories, and this is one of the reasons why many trip planners do not provide these features.

Finally, information on the different graph data structures that will be used to represent the two main data sets in the multi-modal trip planner, the road network and the public transport network were presented, and the alternative methods were compared for their advantages and disadvantages in terms of computational time, memory and implementation and maintenance difficulty. In particular, the two approaches to representing the Public Transport Network, the TEA and TDA, are better than the other in certain circumstances. The TEA is better than the TDA when computation time and ease of implementation is the main priorities, whereas the TDA is better when memory use needs to be minimised or when the timetables need to be maintained in real-time. Two methods for integrating these networks together were also introduced and compared to each other. The Multi-layered Network approach should be faster when computing a single multi-modal trip, however this is offset by its complexity in implementation as the search algorithm needs to be adjusted to work with the extra layers. The Multi-step approach can be used with standard shortest path algorithms, however it requires more computation time for the multiple journey legs that it needs to calculate. This computation time is less of an issue though, if the goal is to provide a number of trip choices to the user.

These analyses will provide a framework for the development and implementation of the algorithms for the multi-modal, multi-objective trip planner.

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