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An Optimal Transportation Routing Approach using GIS-based Dynamic Traffic Flows

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Abstract. This paper examines the value of real-time traffic information gathered through Geographic Information Systems for achieving an optimal vehicle routing within a dynamically stochastic transportation network. We present a systematic approach in determining the dynamically varying parameters and implementation attributes that were used for the development of a Web-based transportation routing application integrated with real-time GIS services. We propose and implement an optimal routing algorithm by modifying Dijkstra's algorithm in order to incorporate stochastically changing traffic flows. We describe the significant features of our Web application in making use of the real-time dynamic traffic flow information from GIS services towards achieving total costs savings and vehicle usage reduction. These features help users and vehicle drivers in improving their service levels and productivity as the Web application enables them to interactively find the optimal path and in identifying destinations effectively.

Keywords: Transportation routing, GIS, Dynamic traffic flow, Optimal path.

1. Introduction

With the development of geographic information systems (GIS) technology, the effective use of such real-time and dynamically changing information gathered have become a common practice in many application areas [19] [20].

The purpose of this paper is to show that real-time traffic information, combined with historical traffic data, can be used to develop routing strategies that tend to improve both cost and service productivity measures. More specifically, motivated by situations where time-sensitive delivery is required, we examine the value of a real-time traffic information technology such as GIS for arriving at an efficient vehicle routing method. Using GIS, the real-time information gathered about the dynamic changes in the traffic flow would serve as the typical constraints to solve a routing problem in a stochastic transportation network. We propose an optimal transportation routing algorithm that caters to these constraints. We also present a systematic approach to aid in the implementation of our proposed algorithm for an efficient road transportation routing system that could be integrated with a GIS providing real-time traffic flow information.

We consider a stochastic shortest path problem on a road network composed of links having non-stationary travel times [1] [6], where subsets of these links are observed for traffic flow in real-time with the aid of a GIS. We assume that each observed link can be in one of two states (congested or un-congested) based on the travel time distribution used in our algorithm. The primary objective of this paper is to answer the following question:

- How should a vehicle be routed optimally through a transportation network, based on real-time dynamically changing traffic flow information?

The rest of the paper is organised as follows: Section 2 provides a literature survey of related work. Section 3 describes the background and setup of the transportation routing problem of this research study. In Section 4, we propose an optimal shortest path algorithm and its real-time implementation as a Web application that incorporates the dynamic traffic flow information with the aid of GIS services. Finally we provide conclusions and future work of this research work in Section 5.

2. Related Work

The classic shortest path problem has been extensively examined in the literature. Fan et al. [2] demonstrated that when the utility function is linear or exponential, an efficient Dijkstra's type algorithm can be used to compute the minimum cost route in a stationary (static) stochastic network. Delling and Wagner [3] showed that standard shortest path algorithms (such as Dijkstra's algorithm [16]) do not find the minimum expected cost path on a non-stationary (dynamic) stochastic network and that the optimal route choice cannot be computed as a simple path but determined based on a policy. This is because there are many dynamically varying parameters that require policy-based decision making [10] [11]. The best route from any given node to the final destination depends not only on the location of the node, but also on the arrival time at that node. The arrival time is determined based on several factors such as, the distance, any road works or diversions present, the traffic congestion and vehicle / driver speed.

Some studies in literature make use of a heuristic approach when a road map is characterized by a tightly interconnected network of nodes as the complexity of finding the shortest path could only be estimated in real-time [7]. Using the A^* algorithm, guided by the distance heuristic, it was shown that a fraction of the nodes expanded under breadth-first search would also be expanded by $A*$. The $AO*$ for a non-stationary stochastic shortest path problem with terminal cost was investigated by Bander and White III [1]. It was shown that AO^* is more computationally efficient than dynamic programming when lower bounds on the value functions are available. Their problem formulation was similar to our model except that the real-time traffic congestion information was not considered.

For the non-stationary deterministic case, Hashemi et al. [4] consider time, transit time and parking time with a corresponding time-varying cost to find the shortest paths. For the same case, Lim et al. [12] developed an algorithm to determine paths between two nodes which optimize a cost function of the delay probability distribution. Miller-Hooks and Mahmassani [9] gave and algorithm for finding the least expected cost path and compared their algorithm for the discrete-time non-stationary stochastic case. Psaraftis and Tsitsiklis [8] considered a problem similar to the one discussed in this paper in which the travel time distributions on arcs evolve over time according to a Markov process except that the changes in the status of the arc are not observed until the vehicle arrives at the arc.

Kim et al. [5] extended the work of Psaraftis and Tsitsiklis [8] to examine the case where the congestion status of each arc is available to the vehicle driver. Systematic state space reduction techniques for non-stationary stochastic shortest path problems with real-time traffic information were provided to improve computation and implementation processes. This paper is an extension of Kim et al. [5] and we examine more comprehensive issues integrating vehicle routing with real-time traffic flow information from GIS.

3. Transportation Routing Problem Setup

The issue of choosing the best routing path for vehicles, when it is time dependent, has been a critical matter in the transportation routing problem, as it involves cost, manpower time and service quality. In general, the shortest path is mistaken for the shortest distance measure without, taking into account other conditions that might delay arrival of the vehicle, such as road congestion. If the shortest road based on distance measure has a traffic congestion, it might be better off to take a route that might seem longer in distance but could really get the vehicles to their destinations faster due to less traffic congestions. Hence, a thorough understanding of the problem scenario is essential for addressing this issue.

In order to arrive at a procedure for determining the optimal vehicle routing with real-time traffic information, we assume the following decision-making scenario. First, we bring the driver in the origin at a predetermine time called *driver attendance time*. Next, we assume the driver is available from the driver attendance time and he begins to get paid from that moment onwards. In practice, the driver attendance time is scheduled and set in advance since the driver may not be available immediately when requested. After bringing in the driver, we need to continuously observe the congestion status of each link and at some point of time we set the actual departure time. This is because, the driver attendance time may be (and often is) different than the actual departure time due to prevailing heavy traffic conditions that make it advantageous to delay departure. After departing the origin, the decision maker must choose the next intersection to visit given the current congestion status of each observed link. Upon reaching the next intersection, or perhaps immediately prior to reaching it, the status of the observed links is again observed and the trip continues.

3.1. Analysis of a real-life problem situation

The best approach to fully understand the problem situation is to study a real-life traffic congestion scenario. This way we believe that we would be able to determine the most important varying parameters that could influence in the decision-making process. We studied the traffic system in the busy and well-known Zarqa city in Jordan, where we collected data from its geographic information center (GIC) over a period of two weeks. Table 1 shows the data of average speed of a vehicle in each 15-minute interval throughout a day based on distance and average congestion.

Each intersection was examined and the distance between edges were calculated with the aid of a digitizing map and we used these information to represent the network as graph containing intersections (nodes) and roads (arcs).

Table 1: Average traffic flow - vehicle speed at loops in each 15-min interval. (Unit: mph)

	Loop number	0:00-0:15	0:15-0:30	0:30-0:45	0:45-1:00	…..	12--12:15
Day 1	1	73	72	72.9	73.82		74.2
	2	59.12	60.21	60.9	59.7		61
	..	..	..	..	..	..	..
Day 2	1	72.02	71.2	71,9	72.3		73.9
	2	60	61	62.2	61.9		61.82
	..	..	..	..	..	..	..

We then performed data analysis, which confirmed that the shortest path based on distance does not always guarantee fastest arrival and many times it was possible through other paths. This data collection and analysis helped us in arriving at the required parameters for the study. We observed that the total cost was directly proportional to distance and traffic congestion and inversely proportional to the vehicle speed.

3.2. Digitizing maps from GIS

The map of Zarqa city (Figure 1) captured in real-time with the Geographic Information System (GIS) is used to generate the network depicting the road transportation network of the city. We convert these maps to the digitized form (Figure 2) using digitizing converters, which store them as digital raster files. Next, these files are imported into ArcCatalog, which does a "raster-to-vector" conversion so that the final output is in a vector format, holding specific information such as streets, blocks, and addresses.

Figure 1:Map from GIS

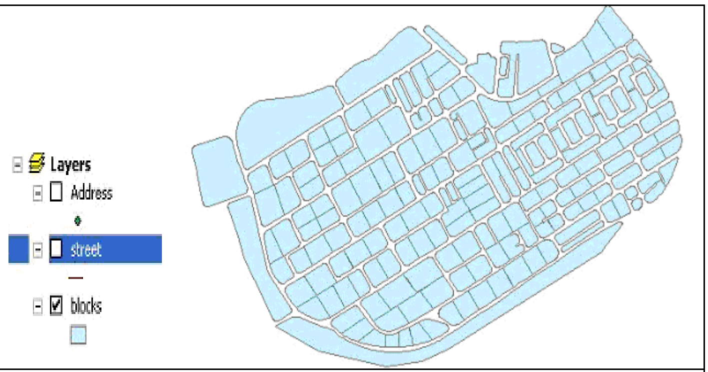

Figure 2: Map after digitizing to raster file format

Table 2: Address and street information retrieved from GIS

FID	Sshape	S_n	B_b_no	S_b_no
0	point	Saqer	2	1
1	point	Karamah	2	1
2	point	Saqer	1	1
3	point	Perin	1	2
4	point	Perin	1	2
5	point	Saqer	4	2
6	point	Saqer	4	1

The address layer represented by point shape and the block layer represented by polygon shape are stored in the database as shown in Table 2 with properties, such as: i) FID as the index of block / point with unique values, ii) Shape that refers to the shape type of this instance, iii) S_N that refers to the street name of the block or point, iv) B_B_NO as the base block number, and v) S_B_NO as the sub-block number.

From these vectors, we then generate the network of nodes and arcs that would serve as an input to our proposed shortest path algorithm and finally this stored information would be used in drawing the shortest path output.

4. Proposed Algorithm and Implementation

The classic shortest path problem with static cost constraints on the arcs have been solved before [2] [14] [16]. We modify Dijkstra's algorithm [16] and propose a new algorithm that takes into account of dynamically changing parameters such as traffic congestion so that real-time traffic information gathered through Geographic Information Systems (GIS) are used effectively for achieving an optimal vehicle routing within a stochastic transportation network. Based on the preliminary analysis of the real-life traffic flow observed in a city as described in previous section, we postulate the following relationships of the varying parameters with the cost associated with each arc:

i) The cost (C_{ij}) is directly proportional to the traffic congestion T_{ij} between two nodes *i* and *j*,
ii) The cost (C_{ij}) is directly proportional to the distance (D_{ij}) between two nodes i and j,
iii) The cost (C_{ij}) is inversely proportional to the vehicle speed (S_{ij}) between two nodes i and j, and
iv) Lastly, the cost (C_{ij}) is directly proportional to some constant factor or weight (W), which is assigned based on certain fixed parameters such as fuel charge, currency rate, road tax etc.

Hence, the cost (C_{ij}) assigned to an arc connecting node *i* and *j* is given by the following equation:

$$C_{ij} = \frac{W(D_{ij}T_{ij})}{S_{ij}} \tag{1}$$

Some of these parameters are obtained from the GIS in real-time, while others could be dynamically retrieved from a database. The objective of our proposed algorithm is to find the shortest path that minimizes the total cost, by calculating the dynamically changing C_{ij} on each arc as given in the above equation. A network N is generated from the GIS service with real-time traffic flow information and we maintain a partition of N into two subsets: Set P containing permanently labeled nodes and set T containing temporarily labeled nodes. The algorithm iteratively moves nodes from T one at a time in non-decreasing order based on the minimum path from the source node, s. We present below the pseudo code of our proposed algorithm by modifying Dijkstra's Algorithm to achieve an optimal route in the network, minimizing the total cost and at the same time catering to the above mentioned dynamic constraints.

```
Function Routing
 BEGIN
     P: = {}; T: = N;
     Initialize tc(i) := ∞
    FOR each node i in N DO
        tc(s) := 0 ;
        pred(s) := 0;
   ENDFOR
```

```
WHILE |P| < n DO
    pick i in T with minimum tc(i) value;
    move i from T to P;
   FOR each (i,j) DO
      IF tc(j) > tc(i) + cij THEN
           tc(j) := tc(i) + cij
           pred(j) := i
        ENDIF
      ENDFOR
   ENDWHILE
END Function
```

Figure 3: Pseudo code of the proposed algorithm for an optimal routing

From previous studies, Dijkstra's algorithm has been reported to give optimal routing paths. Since we have introduced the dynamic traffic flow information attributing to which is calculated in real-time during each FOR-loop of the algorithm, our proposed algorithm would result in an overall reduction in the total cost (Tc).

Implementation attributes considered

We have considered four main implementation attributes reported in literature [17] that could affect the real-time performance of the shortest path algorithm. They are, Network Representation, Node Labeling Method [21], Selection Rules and Data Structures. These attributes are described below:

Network Representation - The way in which an input network is represented and implemented in a shortest path algorithm is vital to the performance of the algorithm [15]. There are several straightforward ways of representing a general network for computational purposes. Past research has proven that the 'Forward Star' representation is the most efficient network representation with two sets of arrays. The first array is used to store data associated with arcs, and the second array is used to store data related to the nodes. All arcs of a transportation network are maintained in a list and are ordered in a specific sequence. That is, arcs emanating from nodes 1, 2, 3, etc., are ordered sequentially. Arcs emanating from the same node are ordered arbitrarily and all information associated with an arc, such as starting node (*i*), ending node (*j*), the distance (D_{ij}), the vehicle speed (S_{ij}) and the traffic congestion (T_{ij}) from GIS are used to dynamically calculated cost C_{ij}, and are stored in corresponding arrays or linked lists).

Node Labeling Method - The node labeling method is a central procedure in shortest path algorithms [17] [21]. The output of the labeling method adopted is an out-tree from a source node, s. This out-tree (an oriented tree in which all vertices are reachable from a single node) is constructed iteratively. The shortest path from s to *i* is obtained upon termination of the iterative procedure and hence improves the performance of the algorithm.

Selection Rules – In our shortest path algorithm, the strategies used to select the next temporarily labeled node are particularly important as they impact the efficiency and speed of computations [13]. Strategies commonly used for selecting the next temporarily labeled node to be scanned are: i) FIFO (First In First Out), where the oldest node in the set of temporarily labeled nodes is selected first, ii) LIFO (Last In First Out), where the newest node in the set of temporarily labeled nodes is selected first, and iii) BFS (Best-First-Search), where the minimum cost label from the set of temporarily labeled nodes is considered as the best node. We have adopted the BFS strategy for the node selection rule.

Data Structures - A number of data structures can be used to manipulate the set of temporarily labeled nodes in order to support these strategies [18]. These data structures include arrays, singly and doubly linked lists, stacks, buckets and queues. The bucket data structure is related to the double bucket implementations of the Dijkstra's algorithms. Buckets are sets arranged in a sorted fashion. Bucket k stores all temporarily labeled nodes whose cost labels fall within a certain range.

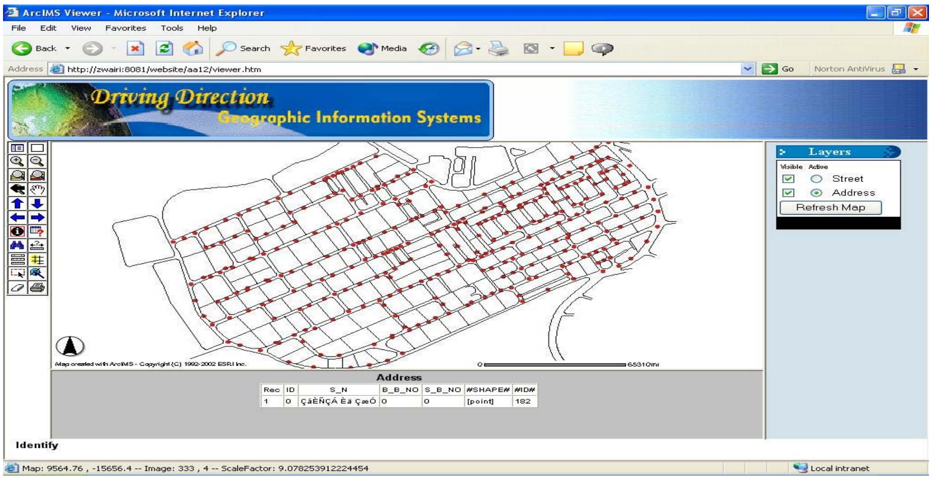

Figure 4: Screenshot of our GIS-based Optimal Transportation Routing Web Application

We have implemented our algorithm within a Web application that enables users to discover the optimal path and in helping with the driving direction between two specific nodes of the shortest path on a digital land map that is integrated with the GIS. A screen snapshot of our Web application is shown in Figure 4. In a nutshell, this application provides the following features:

- To provide the vehicle drivers with the ability to find the optimal path that he/she must follow in order to travel from start point to destination point by highlighting the dynamically generated shortest path over the Web-based digital map.
- To enable the Web application to access, integrate and display the traffic flow data generated from GIS services.
- To assist the vehicle drivers with a Web interface for displaying landmarks and other information in identifying blocks, streets and addresses on the digital maps.

5. Conclusions

This paper provides a systematic approach to aid in the implementation of an optimal transportation routing system that is integrated with GIS technology, which provides real-time dynamically changing traffic flows. From literature, we observe that when the number of network links increases with real-time traffic information, the problem of determining optimal routing path under stochastically changing traffic flows may become intractable. Hence, we studied and analysed the influencing dynamically changing parameters in a particular city that helped in proposing an optimal routing algorithm. In addition, the use of good implementation attributes such as Network Representation, Node Labeling Method, Selection Rules and Data Structures have also facilitated in developing a real-time performance of our algorithm within a Web-based application. Our primary conclusion is that real-time traffic information from GIS incorporated within an interactive Web application can significantly reduce expected total costs, vehicle usage and driver productivity during times of heavy congestion. Our future work entails in measuring these improvements in real-life scenarios.

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