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A GIS-based Dynamic Shortest Path Determination in Emergency Vehicles

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Abstract: Accomplishing an effective routing of emergency vehicle will minimize its response time and will thus improve the response performance. Traffic congestion is a critical problem in urban area that influences the travel time of vehicles. The aim of this study is developing a spatial decision support system (SDSS) for emergency vehicle routing. The proposed system is based on integration of geospatial information system (GIS) and real-time traffic conditions. In this system dynamic shortest path is used for emergency vehicle routing. This study investigates the dynamic shortest path algorithms and offers an applicable solution for emergency routing. The shortest path applied is based on Dijkstra algorithm in which specific rules have been used to intelligently update the proposed path during driving. Results of this study, illustrate that dynamic vehicle routing is an efficient solution for reduction of travel time in emergency routing. Finally, it is shown that using GIS in emergency routing offers a powerful capability for network analysis, visualization and management of urban traffic network. Spatial analysis capabilities of GIS are used to find the shortest or fastest route through a network. These capabilities of GIS for analyzing spatial networks enable them to be used as decision support systems (DSSs) for dispatching and routing of emergency vehicles.

Key words: DSS • Dynamic vehicle routing • GIS

INTRODUCTION

Traffic congestion is perhaps the most conspicuous problem in the transportation network and has become a crucial issue that needs immediate attention [1]. It is commonly recognized that building more infrastructure, which is usually financially and environmentally constrained, is not the only remedy to congestion. Nowadays, traffic measures to relieve congestion are generally based on the concept of making best use of the current infrastructure with advances in information technology, which is the underlying idea of intelligent transportation systems (ITS). Among various sub-systems of ITS, an advanced traveler information system (ATIS) aims to provide travelers with updated and useful information about network conditions, in hope that a better informed traveler can make a better decision and collectively better decisions by many travelers would result in a relief from congestion [2].

Traffic congestion is a major reason that affects the travel time of emergency vehicles and increases the response time of emergency medical services. It is well known that there is a positive relation between ambulance delay and the ratio of fatal to serious injuries. To mitigate this problem, road users, including emergency response vehicles, need to undertake dynamic routing to reach their destinations. Accomplishing an effective routing of ambulance will minimize its response time and thus improve the response performance [3].

The objective of this study is developing a dynamic routing system which guides emergency vehicles through the urban road network considering real-time traffic conditions. This system computes the shortest path based on historical data and updates it using real-time traffic data. In this study recurring congestion modeled as historical data and nonrecurring congestion as a result of unwanted incidents is considered as the real-time data. Another consideration is that needed infrastructure such as GPS, communication link and two way radio is provided. In the context of our study, the term "shortest path" means "minimum time" or "fastest" path between origin and

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destination. We use the term ''routing'' in this study to denote the task to move emergency vehicle from current position to location of emergency request in a given road network.

The shortest path problem, finding the path with minimum distance, time or cost from a source to a destination, is one of the most fundamental problems in network theory. It arises in a wide variety of scientific and engineering problem settings, both as stand-alone models and as sub problems in more complex problem settings. Most of the literatures have focused on the problem in which the link travel cost (or weight) is assumed to be static and deterministic. Many efficient algorithms have been developed by Bellman [4], Dijkstra [5] and Dreyfus [6]. These are referred to as the standard shortest path algorithms.

In the static and deterministic cases of vehicle routing all information is known at the time of planning of the routes. Nowadays, Due to the development of ITS, there has been an increasing interest in the concept of dynamic management of transportation systems. These new advances have brought renewed interest in the study of shortest path problems in which link costs generally are time-dependent. This results in a new family of shortest paths problems known as dynamic, temporal or time-dependent shortest path problem which are referred as DSP, TSP or TDSP problem.

In dynamic version of shortest path the characteristics of network especially the weight of links varies with time. To solve a dynamic shortest path problem, this variation should be taken into consideration. Consider a road network represented by a directed graph consisting of a finite set of nodes and links. Each link in the network has an associated generalized cost which could be a combination of travel time, direct cost and travel distance. Without loss of generality, this study will use travel time to represent this generalized cost. It is assumed that the link travel times in the network are not static and depend on traffic congestion of roads which varies over time.

The development of new telecommunication and computer technologies has made the dynamic routing problem a reality since the required data can be obtained and processed in real–time. For instance the position of vehicles is available in real–time using GPS which can be reported on a map in GIS. In the next section, the concept and literature on dynamic shortest path are described.

Dynamic Network Modeling: In general, a dynamic network is a network whose characteristics change over time. These networks typically fall into one of two main categories. In the first category, the future characteristics of the network are not known in advance. Algorithms which optimize the performance of this type of network are sometimes called re-optimization algorithms, since they must react to changes in network conditions as they occur by making small changes to an existing optimal solution so that it remains optimal under new conditions. In the second category, time-varying network characteristics are known at all times [7].

Due to the two categories of networks, we classify dynamic shortest path algorithms in two classes. First class is named dynamic shortest path (DSP) algorithms which are considered in the first category of networks. Second class is time–dependent shortest path (TDSP) algorithms which are related to second network category. In the following part, we first describe the transportation network and then briefly review algorithms dealing with this network.

Transportation Network: The transportation network is inherently dynamic because the state and measures of traffic change over the time. One of these measures is travel time. Travel time is dynamic due to traffic congestion. Traffic congestion is a huge problem, especially in metropolitan areas. At times of high traffic congestion, the state of the network (traffic flow and density) feasibly varies with time. Hence, the correctness of the shortest path depends upon the correctness of the cost model.

Traffic congestion can be categorized into two basic types including recurring and non-recurring congestion. Recurring congestion is predictable because it generally recurs at the same location on a daily basis. Non-recurring congestion is unpredictable because it is the result of dynamic events. The disturbances to traffic networks, at the result of incidents, vehicle breakdown, bad weather, work zones, special events and so on, cause non-recurring congestion which is a significant part of the total congestion. Some of these disturbances are completely unpredictable, such as incidents and vehicle breakdown. Others are predictable to some extent, such as bad weather, work zones and special events, but usually there are prediction errors.

As the information technology infrastructure becomes more sophisticated, more accurate real-time information about traffic incidents and traffic congestion will be available at all times. The routing instructions could be updated in response to this real-time information concerning recurring and nonrecurring congestion observed within the transportation network [8]. The rapid representation of incidents to user, especially combined with the shortest path routing process, is one of the most effective means of reducing the impacts of such non-recurring events.

Dynamic Shortest Path Algorithms: The dynamic version of the shortest path problem consists of maintaining shortest paths while changes in the graph are performed, without re-computing them from scratch. In such a framework the most general repertoire of update operations includes insertions and deletions of arcs and update operations on the weights of arcs. When arbitrary sequences of the above operations are allowed, it is referred as fully dynamic problem; if it has been considered only insertions (deletions) of arcs then it is referred as incremental (decremental) problem [9]. In some papers [10-11] incremental (decremental) problem is referred as semi dynamic problem.

Dynamic shortest path problem finds applications in many areas including transportation networks, where weights are associated with traffic/distance; database systems, where one is often interested in maintaining distance relationships between objects; data flow analysis and compilers; document formatting; and network routing [12]. Many solutions have been proposed in the literature to deal with (fully and semi) dynamic shortest path problems both for single-source and all-pairs versions [10].

Among the algorithms proposed for the DSP problem, the algorithm of Ramalingam and Reps (RR) [1] seems to be the most used. It is a fully-dynamic DSP algorithm which updates the shortest paths incrementally. One of its main advantages is having good performance in most situations; however it is not the best algorithm for all applications [13]. In the case of planner graphs, a fully dynamic solution for maintaining all-pairs shortest path with unrestricted edge weights has been proposed in [14], but the proposed algorithm is complex and far from being practical [10].

An efficient solution for the all-pairs incremental problem has been proposed in [15], when the edge weights are integer in the range [1..C]. An efficient decremental solution for the single source version of the problem on digraphs, with integer edge weights in [1..C], has been given in [16]. Frigioni *et al*. [10] perform experiments on the fully dynamic single source shortest path problem on directed graphs with positive real edge weights. They propose an experimental analysis of three different algorithm: dijkstra's algorithm and two output bounded algorithms by Ramalingam and Reps[1] and by Frigioni *et al*. [17]. Demetrescu *et al*. [18] present the results of an extensive computational study on dynamic algorithms for all pairs shortest path problems. He describes implementations of the recent dynamic algorithms of King [19] and of Demetrescu and Italiano [12] and compares them to the dynamic algorithm of Ramalingam and Reps [1] and to static algorithms on random, real-world and hard instances. His experimental data suggests that some of the dynamic algorithms and their algorithmic techniques can be really of practical value in many situations.

Time Dependent Shortest Path Algorithms: TDSP algorithms consider the problem of computing shortest paths through a network with time-varying characteristics, such as arc travel times and costs, which are known for all values of time. In dynamic transportation networks, weight changes can be classified as either deterministic or stochastic time-dependent. In the deterministic time-dependent shortest path (TDSP) problem, the link-weight functions are deterministically dependent on arrival times at the tail node of the link, i.e., with a probability of one. In the stochastic TDSP problem, the link-weight is a time-dependent random variable and is modeled using probability density functions and time-dependency [11].

TDSP problem was initially proposed by Cooke and Halsey [20] in 1966, which is a modified form of Bellman's label [4] correcting shortest path algorithm. It discretizes the time horizon of interest into small intervals. The algorithm starts from the destination node and then calculates the path operating backwards. This problem can be seen as the first deterministic time-dependent shortest path algorithm, where the link delay functions are deterministically dependent on arrival times at the tail node of the links. Since then, several authors have proposed alternative solution algorithms for some variants of the discrete-time dynamic shortest path problem. In 1997, Chabini [21] proposed a theoretically optimal algorithm for solving the basic all-to-one dynamic shortest path problem. Pallottino and Scutella [22] provide additional insight into efficient solution methods for the all-to-one and one-to-all problems. Chabini and Dean [23] present a detailed general framework for modeling and solving all common variants of the discrete-time problem, along with a complete set of solution algorithms with provably-optimal running time.

Hall [24] investigated the shortest path problem in a transportation network where the link travel times are random and time-dependent and demonstrated that the standard shortest path algorithm may fail to find the expected shortest path in these networks. He worked on the stochastic TDSP problem and showed that one cannot simply set each link-weight random variable to its expected value at each time interval and solve an equivalent TDSP problem. Miller-Hooks and Mahmassani [8] provide an algorithm for finding the least expected cost path in the discrete-time STDSP problem. Chabini and Gao [2] studied optimal routing policy in stochastic time-dependent networks, where link travel times are modeled as random variables with time-dependent distributions. The significant previous algorithmic results in the literature related to the continuous-time dynamic shortest path problem are due to Orda and Rom [25-26] and Dean [7].

MATERIALS AND METHODS

This study offers an applicable solution for dynamic routing of emergency vehicles. It proposes a routing system that uses historical traffic data to model recurring congestion and computes initial shortest path. As unpredicted (nonrecurring) congestion occurs and is reported from traffic control center, the system analyzes the real-time data to determine if the planned route needs to be modified. It can modify the planned route as a function of the current position, destination location and real time traffic condition.

Overall System Framework: The proposed routing system has been composed of three subsystems including positioning system, communication system and GIS (Fig. 1). The subsystems are explained below.

GIS Subsystem: GIS is a computer-based information system that enables the capture, modeling, manipulation, retrieval, analysis and presentation of geographically referenced data. GIS has become an important technology for many applications and disciplines. The integration of various application models into GIS has enabled users to go beyond the data inventory and management stage to conduct sophisticated modeling, analysis and visualization for spatial decision-making. The rapid developments of GIS applications and wireless technologies in the navigation, tracking and mobile mapping systems have increased the demand for up-to-date geospatial information and GIS [27].

GIS facilitates modeling of spatial networks (e.g. road networks) and provides effective tools for querying spatial and attribute data, displaying maps and performing spatial analysis tasks. Spatial networks are modeled with graphs. In the case of road networks, the graph's arcs correspond to street segments whereas the nodes correspond to street segment intersections. Each arc has a weight associated with it, representing the impedance (cost) of traversing it. In this study, an arc's impedance is a travel time for traversing that arc. A GIS usually provides a number of capabilities for the analysis of spatial networks. It generally offers tools to find the shortest or minimum impedance route through a network. These capabilities of GIS for analyzing spatial networks enable them to be used as decision support systems for the dispatching and routing of vehicle [28].

GIS technology is beginning to be used by health agencies in the planning of EMS deployment. GIS provides EMS planners with the ability to organize and manipulate large volumes of spatially referenced call data

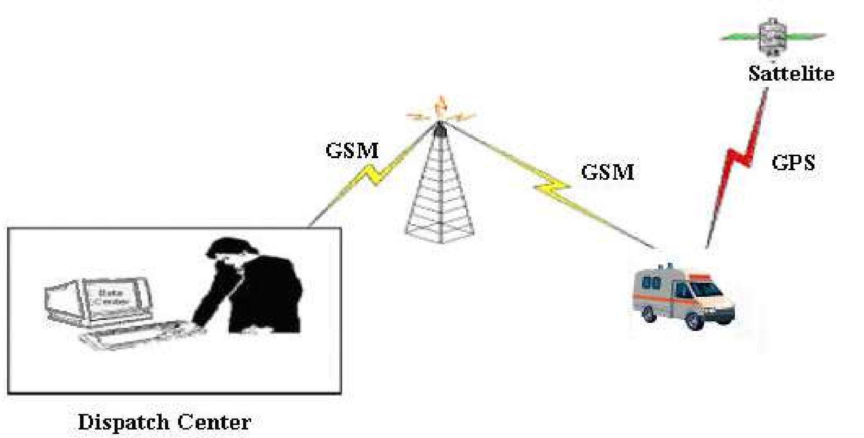

Fig. 1: The proposed system architecture

and to communicate spatial concepts to decision makers responsible for service deployment planning. Using GIS, decision makers are able to visualize data in map form and understand geospatial patterns and trends in ambulance response performance that would otherwise be difficult to ascertain [29].

GIS aids emergency medical response considering the followings:

- Identifying emergency call locations
- Providing dispatchers with closest available unit information
- Determining the quickest route to the call and appropriate medical facilities
- Analyzing incident volumes and trends for staffing purposes
- Tracking disease outbreaks

Positioning Subsystem: The Global Positioning System (GPS) is a U.S. space-based radio navigation system that provides reliable positioning, navigation and timing services to civilian users on a continuous worldwide basis - freely available to all. For anyone with a GPS receiver, the system will provide location and time. GPS provides accurate location and time information for an unlimited number of people in all weather, day and night, anywhere in the world.

There are other methods for position determination with the mobile cellular phone, which are based on the determination of position relative to the base station or transmitter. In the third generation cellular phones, it is possible to determine the location of any mobile phone subscribed anywhere, any time and without combination with other sensors such as GPS. The precision obtained by GSM network for position determination is not good enough compared to GPS, mainly due to the measurement noise and multipath propagation problems in GSM systems [27]. The proposed system uses GPS tracking or some other suitable location monitoring and tracking system to know the current location of emergency vehicle.

Communication Subsystem: GSM is a digital cellular communication system that is the most popular second generation (2g) cellular system in the world. One of the popular GSM services is the Short Message Service (SMS) that allows users to send and receive point-to-point alphanumeric messages up to a few tens of bytes. The SMS service provides a basic tool to transfer data used to estimate position or coordinates of the mobile station. Because of the limited data transfer in the GSM, new technologies have been developed on top of GSM such as the (2.5g) GPRS and the third generation (3 g) cellular system Universal Mobile Telecommunications System (UMTS). GPRS is emerged to optimize the Internet/Intranet access capabilities. GPRS is a new IP-based technology of packet data transmission in a mobile communications network [27-29].

However, a communication system is needed to establish a communication link between the vehicle and the dispatcher. It deals with the sent and received data from/to vehicle. The vehicle data transmitted through communication system include the current position of the emergency response vehicle, progress of the emergency response vehicle along with the planned route and vehicle operational characteristics. After updating a route, modification of planned route and decision point (nearest junction) send to vehicle via communication system. Further, this system provides data transmission between traffic control center and emergency management center.

Case Study: A digital road network in a small area of Tehran, capital of Iran, was used within the GIS map at a scale of 1:2000. The road network was represented as connections of nodes and links. Geometric networks are built in the GIS model to construct and maintain topological connectivity for the road data in order to allow the path finding analysis to be possible. In order to plan the initial shortest path, we use historical data of average traffic volume at surface streets or freeway segments within the area under study. The segment lengths have been extracted using ESRI’s ArcGIS 9.0 software. The average volume of each link in the network has been obtained from Tehran Traffic Center. Then Bureau of Public Roads (BPR) model has been used to estimate travel time for the particular segment. Summation of the travel times for all segments of a particular path between origin and destination provides the total travel time, which is minimized by the shortest path algorithm. The routing macro use Dijkstra’s routing algorithm with d-heap (d=2) data structure to compute shortest path.

The dispatcher enters an address of the desired destination and the system, using maps and sophisticated routing software, computes the fastest or shortest path based on historical data. The vehicle starts to move through this shortest path. The location of the moving vehicle is determined via GPS receiver and the GSM system is used to transmit the location to the base station via the SMS or the General Packet Radio Service (GPRS). The real time traffic information is provided in dispatch center. The dispatcher aided by the developed routing

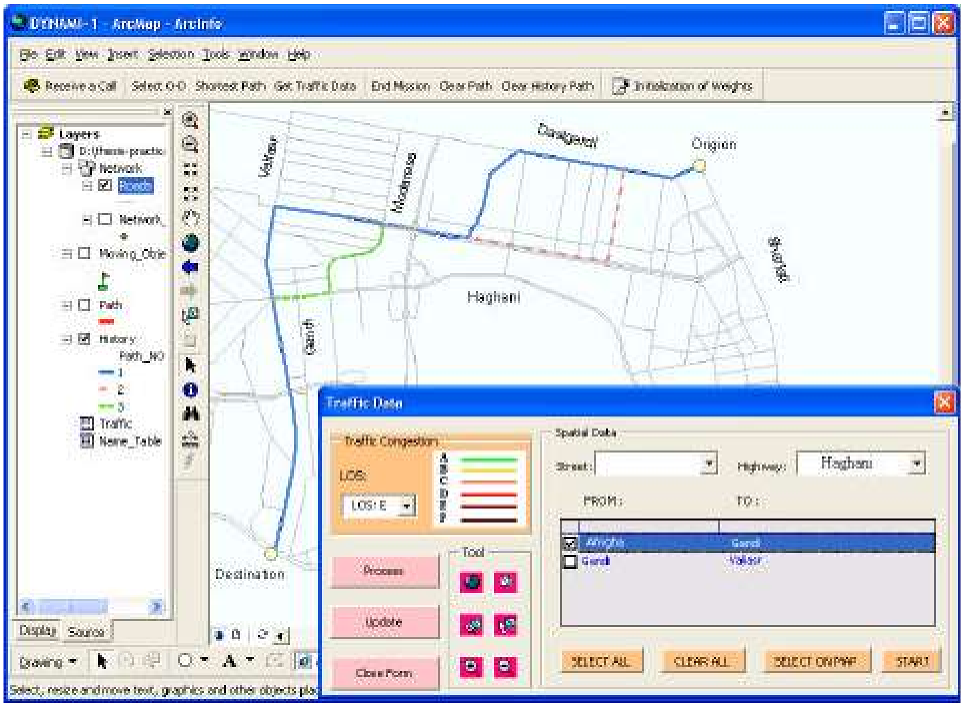

Fig. 2: Shortest path update, the dashed lines are new segments after updating

system and customized software, presents an accurate picture of where non-recurring and recurring congestion exist at any time. The routing system analysis real time traffic data and vehicle location to determine if the planned route need to be modified. If the result of process is true, the system updates the planned route based on this real time data. The updated route is send via communication system to vehicle driver to change his route. This process continues until the mission of emergency ends and the emergency vehicle goes back to the dispatch center (Fig. 2).

CONCLUSIONS AND RECOMMENDATIONS

This study addresses the problem of determining dynamic shortest path in traffic networks, where arc travel times vary over time. This study proposes a dynamic routing system which is based on the integration of GIS and real-time traffic conditions. It uses GIS for improving the visualization of the urban network map and analysis of ambulance routing. GIS is used as a powerful functionality for planning optimal routes based on online travel time information.

The results of this study illustrate that dynamic routing of emergency vehicle compared with static solution is much more efficient. This efficiency will be most important when unwanted incident takes place in roads and serious traffic congestion is occurred. In this study, the initial planned route is saved since when real-time data is received only portion of the planned path may be changed. This improves the computational performance than re-computing from scratch. This is the main idea of dynamic shortest path algorithm. Developing a dynamic routing system for all vehicles in urban road network has some special considerations which is the subject of our future work.

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