An Optimization Model for
Real-Time Emergency Vehicle Dispatching and Routing

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ABSTRACT

The efficiency of Emergency Medical Service (EMS) system is a major public safety concern. When real-time traffic and travel time data are available to EMS dispatch center, a real-time and flexible dispatching strategy could be used to save crucial response time for EMS. This research concentrates on developing an optimization model for developing flexible dispatching strategies that take advantage of available real-time travel time information. The problem is formulated as an integer programming model in which a dynamic shortest path algorithm is used. Emergency vehicles and incidents are divided into categories so that different constraints could be incorporated.

A simulation experiment demonstrates how this formulation works under real-time traffic conditions. The major modules of this simulation model include travel time prediction, dynamic shortest path, incident/vehicles tracking, and dispatch optimization. This simulation model is a conceptual design of a real-time EMS system. The real-time dispatch strategy, a key component of this simulation model, is validated by various samples. A series of tests verify the validity of the model structure and the sensitivity of the integer programming formulation to changes in various parameters.

Key Words: Dispatching, Routing, Emergency Response, Optimization, Simulation, Vehicle Assignment
1. INTRODUCTION

The public's concern for safety has generated a need for improved coordination and information sharing between numerous public safety and transportation agencies. These agencies are also becoming interested in developing partnerships that will allow them to share limited resources towards the common goal of improving safety for their customers.

A very real challenge in this initiative to improve transportation system management is to improve the coordination of activities of agencies that play key roles in transportation management. In particular, it is essential to achieve integrated decision-making between state and local transportation agencies and state and local public safety agencies (usually police, fire, and EMS).

In the Emergency Medical Service system, the response time plays a crucial role in minimizing adverse impacts. Fatalities and the loss of property can be greatly reduced by improving the response time to incidents. Incorporating the historical and real-time transportation information with EMS dispatch could increase the performance of the EMS system.

With the advent of Intelligent Transportation Systems (ITS), real-time traffic information will soon be available to emergency dispatch centers. Research is proposed to develop and evaluate a real-time emergency response system that uses real-time travel time information and assists emergency response vehicle dispatchers in assigning the appropriate response vehicles and guiding these vehicles through the best routes so that the system could achieve optimal performance.

This research is focused on developing a system for real-time EMS management. The research aims to develop a mathematical model for decision making in real-time dispatching. The model will be formulated as a mathematical optimization problem. The computational time is a major issue in this model to be applicable in real-time situation, so the computational efficiency will be examined.

This model will be tested in a simulation framework that integrates real-time transportation information with the dispatching process. The simulation model is able to characterize the response mechanics of the dynamic response system and allows for flexibility in dispatching decision making. A simulation model for this purpose is developed by the authors (Haghani et al., 2002). The real-time emergency response system and various dispatching strategies are tested within this simulation framework. The sensitivity of the optimization model results with respect to changes in its important parameters will also be tested within this framework.

The proposed EMS system enables en-route diversion under a series of constraints. A mathematical program will help the dispatcher to make the decision. Although there are a number of EMS models, to the best of the authors’ knowledge, none of them allows such great flexibility.

The dispatch model uses a dynamic shortest path algorithm in the mathematical programming formulation. A proper algorithm is selected to compute the shortest path between each related O/D pair. A simulation framework will integrate the mathematical programming formulation and the dynamic shortest path algorithm into the proposed EMS system.
2. LITERATURE REVIEW

EMS systems have been an attractive subject for operations research specialists and management scientists. Work in emergency vehicle dispatching has generally involved the use of three approaches: queuing, mathematical programming, and simulation. In most of the literature on EMS systems, the studies always focus on location, fleet size, and operations performance.

The majority of EMS mathematical models can be categorized into the following topics:

1. Location of ambulance stations or individual ambulances within a region, subject to some performance criteria such as response time (Toregas et al., 1971);
2. Determination of the minimum number of ambulances required to cover a given area;
3. Dispatching strategies and their influence on performance results and services for emergency patients. This method is not applicable to the proposed real-time EMS vehicle dispatching model.

Among researches using queuing methods, Larson conducted significant research on EMS systems. Larson (1974, 1975) used a hypercube queuing model as a tool for facility location and redistricting in urban emergency services.

Developing analytical methods (mathematical programming and queuing models) for EMS system is a rather unrewarding task. Even if we succeed in building an appropriate sophisticated, analytical model, it may not be possible to solve the model using known analytical techniques. This limitation could be overcome if we use simulation to represent the EMS system and its performance. Application of simulation models enables us not only to find an optimal solution to an EMS decision problem, but also to observe an EMS system under different sets of assumptions applied. It also allows us to test new operational strategies such as different ambulance locations or dispatching rules.

Savas (1969) used simulation as a tool to perform a cost-effective analysis of New York City’s emergency ambulance service. Lubicz et al. (1987) set up an EMS simulation model for rural areas in Poland. The simulation is event-based. The distinguished events in the model are the arrival of a new call, the end of service on the scene, and the arrival of patients in hospitals. To evaluate the emergency vehicle base locations for Tucson, AZ, Goldberg et al. (1990) together with Tucson Fire Department, developed a simulation model. The issues of model development, data collection, model validation and experimentation are discussed in this paper. The basic structure of their simulation model is a multi-server queuing system. The simulation serves calls on a first-come-first-served basis since the model does not consider priority scheduling of calls. Goldberg (1991) later formulated an optimization model that extends the previous work by allowing for stochastic travel times, unequal vehicle utilizations, various call types, and service times that depend on call location.

The proposed real-time EMS model is different from the existing EMS models because it incorporates the following characteristics that the existing models lack:

- The existing dispatching models or simulation models do not use real-time traffic information in EMS dispatching. Real-time traffic information will be used in the proposed EMS dispatching model to make dispatch decisions.
- Flexible assignment strategies (en route diversion and reassignment) are not considered in existing models. It can be envisioned that proper en route diversion or reassignment will improve the performance greatly especially when there is significant traffic congestion or when severe incidents happen. In those extreme situations, flexible dispatch will have advantages.
• A queuing and searching method is used to make the dispatching decision in existing models. It is envisioned that a system-wide mathematical optimization will help improve the efficiency of the EMS operations.

A real-time EMS dispatching model must rely on solving a dynamic shortest path problem. Shortest path problems are by far one of the most fundamental and the most commonly encountered problems in the study of transportation and communication networks. Deo and Pang (1984) made a thorough classification scheme as well as a more comprehensive and updated bibliography. In the deterministic Time-Dependent Shortest Path (TDSP) problem, the link-delay functions are deterministically dependent on arrival times at the tail node of the links. The first paper dealing with the time-dependent shortest path algorithms appears to be by Cooke and Halsey (1966). Their algorithm is based on the general Bellman’s principle of optimality. It discretizes the horizon of interest into small time intervals. Starting from the destination node, it calculates the path operating backwards. Ziliaskopoulos and Mahmassani (1993) introduced Cooke and Halsey’s algorithm to calculate the time-dependent shortest paths from all nodes in the network to a given destination node for every time over a given time horizon in a network with time-dependent arc costs.

Dynamic shortest path algorithms depend on travel information of links such as the travel time on link starting from the node at some time later than current time. Therefore, a proper travel time prediction method should be identified so that the dynamic shortest path could have a base on which to work.

The existing prediction methodologies include system wide method and statistical method. The system wide dynamic approach is based on a dynamic traffic assignment model, working in connection with dynamic O/D prediction method. This method will be more accurate for prediction horizons in the range of 15 to 30 minutes. The statistical models use the data collected in the links with explicit prediction errors feedback. It is expected that statistical model are more accurate for short time periods (1 to 10 or 15 minutes). Ben-Akiva et al. (1995) have shown that the statistical model outperforms the dynamic traffic assignment model for shorter prediction horizons.

3. MODEL DEVELOPMENT

3.1. Optimization Modeling Framework for Real-time Dispatching

The proposed framework for the real-time EMS simulation is shown in Figure 1. This model incorporates the dynamic shortest path algorithm and the mathematical programming for dispatching decision. Two random generation modules are traffic generation and incident generation. Traffic generation module creates the real-time traffic information. The incident generation module generates the incidents in the network. In the real world implementation these modules can be replaced by available real-time information. The incidents generated mimic the arrival of emergency calls at the dispatch center.

The traffic information is used to predict the future traffic conditions or travel times, and then calculate the dynamic shortest paths. When the dispatching module receives the real-time shortest paths, incident information and vehicle information, a mathematical programming model is used to find the optimal dispatching and assignment of the EMS vehicles. The locations of the EMS vehicles are determined by their routes and the traffic conditions. The status of incidents are directly related to the activities of the EMS vehicles.
3.2. Characteristics of Emergency Incidents

Severity
Emergency incidents are divided into several types according to severity. In the proposed model, incidents are categorized into 5 priorities, referred to as the incidents with the 1st priority, 2nd priority, etc. \( k(j) \) denotes the probability of incidents with the \( j^{th} \) priority. 
\[
\sum_{j} k(j) = 1, k(j) \geq 0.
\]
\( K(n) = \sum_{j=1}^{n} k(j) \).

Arrival Rates
The total number of incidents happening in the entire study area during a day can be considered as a random number. An analysis of the EMS data for Arlington County, Virginia shows that the total number of incidents per day is a random variable that can be approximated with a normal distribution.

Time Intervals
Usually, the distribution of inter-arrival times can be approximated by an exponential distribution. In another word, the arrival of incidents is a Poisson process.

Location
An emergency incident could happen at any point in the study area. To simplify the problem, the whole region is partitioned into zones with approximately the same area. Usually the study region is divided according to the geographic characteristics and distinguishable population zones. The incidents that happen in each zone are assumed to happen at the central point (median) of the zone.

The Detection Time
This is the time measured from the incident occurrence to the time that the related EMS dispatching center is informed about the incident. Once an incident has been generated, the next process is to simulate detection time. Given the complexity of the access problem and the unavailability of representative data, the detection time is represented as a random variable with normal distribution.

Required Response Time
In 1974 the Emergency Medical Service Act was passed by congress, which mandated that 95% of all calls for emergency medical service must be responded to within 10 minutes in an urban area and 30 minutes in a rural area. In this research the response time is defined as a function of severity. The incident with higher severity and priority should be dealt within shorter response time.

On-the-scene Treatment Time
After the EMS unit arrives on the scene, the EMS team spends some time to treat the patient on the scene. The treatment time for each incident is a function of the severity of incident.

The Need for Hospital Treatment
According to the type and severity of the incident, the EMS team may decide to transport the patient to a hospital. They also may determine the hospital to which the patient is transported. Sometimes the patients may refuse transport.
Geographic distribution

It is assumed that incidents happen in each zone \( i \) with some probability \( f(i) \), \( i \) is the index of the zone. \( \sum_i f(i) = 1, f(i) \geq 0 \). The number of incident in each zone is \( N \cdot f(i) \), where \( N \) is the total number of incidents happening in the entire study area. The generation of incidents is a series of independent processes and the underlying assumption is that various characteristics of each incident are independent.

3.3. Characteristics of the EMS Vehicles

Location

Because the proposed simulation model updates the information from time to time and possibly makes decision at any time, the location of each EMS vehicle must be traced throughout the simulation process. At simulation time \( t \), the EMS vehicle could be either on a node or a link. Methods to indicate the location of EMS vehicle can be static or dynamic as shown in Figure 2.

In the static method the links are divided into several sections and additional nodes are added between those sections. The location of vehicle, then, could be denoted by the node that is closest to the vehicle. In application if the link is divided into few sections, using the node closest to the EMS to express its current location is not very accurate. Therefore, smaller section length is desired. Hence, the total number of nodes in the whole network would increase. Consequently, in the static method to denote the location of the EMS vehicles a significant number of nodes must be added but only a few of them are used.

Alternatively, nodes can be added and deleted dynamically. A node is attached to each EMS vehicle. If the vehicle is traveling on a link, a virtual node is added to that link. The virtual node is connected to the existing node by directed links according to the current movement direction. This is because the EMS vehicles cannot turn around on the link. If the vehicle happens to be right at a node, the virtual node coincides with the existing node.

Destination/Route

The destination is the next station at which the EMS vehicle will stop. Destination can be an incident node, a hospital, or the vehicle’s home station. The route is the path a vehicle will follow from its current location to its destination. If a vehicle is staying at some node, its destination is the node at which it is staying. For the purpose of tracing the location of EMS vehicles, their route will be recorded during the simulation process.

Status

The simulation model categorizes the vehicles according to their current status.

Type 1: Waiting for command at home station;
Type 2: Moving to an incident point;
Type 3: Staying on the scene to treat an incident;
Type 4: Transporting patient to a hospital;
Type 5: Staying at hospital;
Type 6: Moving back toward home station.
3.4. Dispatch Strategy

Two definitions used in the remainder of the paper are stated here in advance. If a vehicle’s destination is different before and after a simulation point, the vehicle has undergone a Route Change. If a vehicle is dispatched to a waiting incident and its destination is different before and after a simulation point, the vehicle has undergone a Reassignment.

At each simulation point, the dispatcher makes a dispatching decision for the EMS vehicles so that the system could use its resources with maximum efficiency. We assume at this point the travel time for each link is predicted and the shortest path for each pair of nodes is known based on the link information. The strategy developed in this section will help the dispatcher to determine the next destination and the route for each EMS vehicle. Depending on the current status of the vehicle the possibility for status changes are summarized in Table 1.

Under the objective of minimizing the total response time, the route and the destination of the EMS vehicles could change frequently. Too many and too often changes in the destination or route can be confusing and counter productive. It is helpful to introduce a Reassignment Condition into the formulation.

For example, the fluctuation of traffic flow may result in some undesired route change as shown in Figure 3. Before the reassignment vehicle 1 is assigned to an incident at node A, and vehicle 2 is assigned to an incident at node B, \( t_{1,A} + t_{2,B} < t_{1,B} + t_{2,A} \). Under new traffic conditions \( t'_{1,A} \) and \( t'_{2,B} \) increase. If \( t'_{1,A} + t'_{2,B} > t_{1,B} + t_{2,A} \), the result of reassignment could be that vehicle 1 is assigned to node B and vehicle 2 is assigned to node A. If the increase in travel time \( t_{1,A} \) and \( t_{2,B} \) is minor (for example less than 5%), \( (t'_{1,A} + t'_{2,B}) - (t_{1,B} + t_{2,A}) \) is a very small amount and maybe is less than the error of travel time prediction. This kind of route change should be avoided. Rules are established to avoid reassignments or route changes that result form above situations.

**Rule 1** The destination change from home station to incident will have no constraints. The constraints will be imposed on vehicles that are in the status 2 depicted in Table 1.

**Rule 2** Vehicles in status 2 could change to a new destination only if there are significant improvements in the system. Significant improvement is defined as (The new overall response time) - (The old overall response time) > some pre-specified amount of time.

**Rule 3** The drivers will not change route even if the destination is kept the same unless significant improvements could be achieved.

These rules define the condition of reassignment and route change. A mathematical formulation is developed to determine the destination change only. The solution of the mathematical programming problem will determine whether or not the EMS vehicles have to change destinations. The route change is determined by solving a dynamic shortest path problem.

3.5. Mathematical Formulation

The mathematical formulation for the real-time emergency response vehicle dispatching problem minimizes the overall response time subject to vehicle availability and service constraints and is as follows:
\[\text{Min } \sum_{i=1}^{5} d_i \sum_{j=1}^{N} \sum_{v=1}^{N_v} x_{ij} t_{ij}(t) + b \sum_{i=1}^{N} \sum_{k=1}^{N_k} x_{ik} t_{ik}(t) + c \sum_{i=1}^{N} \sum_{s=1}^{N_s} x_{is} t_{is}(t)\]

\[\text{S.T.}\]
\[\sum_{j \in W^1 + ... + W^5} x_{ij} + \sum_{s=1}^{N_s} x_{is} = 1 \quad \forall i\]  
(1)
\[\sum_{j \in W^1 + ... + W^5} x_{ij} = 1 \quad \forall i \in V^1, V^6\]  
(2)
\[\sum_{j \in W^1 + ... + W^5} x_{ij} = 1 \quad \forall i \in V^2\]  
(3)
\[x_{ij} = x_{ij}^0 \quad \forall i \in V^3, V^5\]  
(4)
\[\sum_{k=1}^{N_k} x_{ik} = 1 \quad \forall i \in V^4\]  
(5)
\[\sum_{j=1}^{N_w} x_{ij} = 1 \quad \forall j \in W^0, W^1, ..., W^5\]  
(6)
\[\sum_{i=1}^{N} x_{ij} t_{ij}(t) = T_j(t) \quad \forall j \in W^1, ..., W^5\]  
(7)
\[-\left(\sum_{j \in W^1 + ... + W^5} t_{ij}(t) x_{ij}^0 - \sum_{j \in W^1 + ... + W^5} t_{ij}(t) x_{ij} - \tau\right) \leq M \cdot y_i \quad \forall i \in V^2\]  
(8)
\[1 - \sum_{j \in W^1 + ... + W^5} x_{ij}^0 x_{ij} \leq M (1 - y_i)\]

where:

\(V\) The set of Emergency Medical Service (EMS) vehicles in the system
\(N_v\) The total number of EMS vehicles
\(i\) The index of vehicles in set \(V, i = 1, 2, ..., N_v\)
\(V^1\) The subset of the EMS vehicles in \(V\) that are staying at home station with “idle” status
\(V^2\) The subset of the EMS vehicles in \(V\) that are moving to an incident point
\(V^3\) The subset of the EMS vehicles in \(V\) that are staying at specific points to deal with incidents
\(V^4\) The subset of the EMS vehicles in \(V\) that are leaving for hospitals after finishing the tasks at incident points
\(V^5\) The subset of the EMS vehicles in \(V\) that are staying at hospitals
\(V^6\) The subset of the EMS vehicles in \(V\) that are moving back to home stations
\(W\) The set of incidents that are waiting for EMS vehicles
\(N_w\) The total number of incidents that are waiting for EMS vehicles
\(j\) The index of incidents in set \(W, j = 1, 2, ..., N_w\)
\( W^0 \) The subset of incidents in \( W \) that are currently being treated by some EMS unit
\( W^1 \) The subset of incidents in \( W \) that are waiting for treatment with 1st priority
\( W^2 \) The subset of incidents in \( W \) that are waiting for treatment with 2nd priority
\( W^3 \) The subset of incidents in \( W \) that are waiting for treatment with 3rd priority
\( W^4 \) The subset of incidents in \( W \) that are waiting for treatment with 4th priority
\( W^5 \) The subset of incidents in \( W \) that are waiting for treatment with 5th priority
\( a_i \) The weight of response time for incidents with \( i \)th priority.
\( H \) The set of hospitals in the system
\( N_h \) The total number of hospitals
\( k \) The index of hospital in set \( H, k = 1, 2, ..., N_h \)
\( S \) The set of EMS home stations
\( N_s \) The total number of home stations
\( s \) The index of home station in set \( S, s = 1, 2, ..., N_s \)
\( x_{ij}^0 \) =1 if the a vehicle \( i \) was dispatched to an incident \( j \); =0 otherwise
\( x_{ik}^0 \) =1 if the a vehicle \( i \) was dispatched to hospital \( k \); =0 otherwise
\( x_{is}^0 \) =1 if the a vehicle \( i \) was going back to its home station \( s \); =0 otherwise
\( x_{ij} \) =1 if the a vehicle \( i \) is dispatched to an incident \( j \); =0 otherwise
\( x_{ik} \) =1 if the a vehicle \( i \) is dispatched to hospital \( k \); =0 otherwise
\( x_{is} \) =1 if the a vehicle \( i \) is going back to its home station \( s \); =0 otherwise
\( T_j(t) \) The required response time for incident \( j \) at time \( t \) (see Section 3.2).
\( t_{ij}(t) \) The predicted travel time for vehicle \( i \) to arrive at incident \( j \) while departing at time \( t \)
\( t_{ik}(t) \) The predicted travel time for vehicle \( i \) to arrive at hospital \( k \) while departing at time \( t \)
\( t_{is}(t) \) The predicted travel time for vehicle \( i \) to arrive at home station \( s \) while departing at time \( t \)

The total weighted travel time is the objective function of this formulation. The total travel time includes: the travel time to the incidents waiting for treatment, the travel time to the hospitals, and the travel time to home station. The objective function gives higher weights to incidents with higher priority so that the severe incidents would be served quicker.

Traditionally, in set-covering formulations only the travel time to reach incidents is considered in the objective function to optimize EMS vehicle location and allocation problem. The objective function of this formulation includes the travel time to incidents since this travel time is always crucial for the EMS system. It includes the travel time to hospitals or home station as well. In traditional models the travel times to hospitals or home are either ignored or cannot be optimized since route changes are not allowed there. In a real-time dispatching strategy, it is possible that an EMS vehicle changes to a new hospital destination because the traffic condition on route to its current designated hospital becomes worse. Travel time to home station is less
important but it is included in the objective function and optimized in the formulation so that the system can utilize its resources as efficiently as possible.

Constraints 1 state that every EMS vehicle must have a destination after assignment at time \( t \). The destination of any EMS could be either an incident, or the hospital or the home station. If an EMS vehicle is staying at its current location its new destination will remain the current node.

Constraints 2 ensure that EMS vehicles that are staying at their home stations \( (V^1) \) can be only dispatched to an incident or remain at their current home station(s). The EMS vehicles cannot be dispatched to a hospital without going to an incident first.

Constraints 3 state that the vehicles that are dispatched to incidents \( (V^2) \) will continue going to their previous destination or another incident in the network. They cannot go back to their home station without finishing any job in their trips.

Constraints 4 ensure that vehicles that are dealing with incidents at some incident points cannot be dispatched to any other incident.

Constraints 5 state that the vehicles driving to hospitals can change their destination, but their new destination should be another hospital.

Constraints 6 state that one vehicle must be dispatched to an incident waiting for service. If the number of incidents is greater than the available number of vehicles at some time point \( t \), a pre-processing will be done. Some incidents with lower priorities and later arrival times will be put in a queue. This pre-processing ensures that the number of vehicles is greater than or equal to the number of incidents waiting for service so that the formulation has a feasible solution.

Constraints 7 ensure that although we are trying to optimize the total weighted travel time, every incident is treated justly. The bottom line is that each incident should be reached in some required response time so that the service standard could be met.

Constraints 8 are mathematical expressions of the reassignment conditions that were discussed in Section 3.4. \( y_i \) is an indicator variable. If a vehicle \( i \) is assigned to a new destination, \( y_i \) is equal to 0, otherwise \( y_i \) is equal to 1. The condition of reassignment is that the travel time to the new destination incident is less than the travel time to previous destination by a threshold \( \tau \).

### 3.6. The Conceptual Simulation

A simulation model is developed that incorporates all issues discussed so far Haghani et al. (2002). At each simulation point, the program will update the accident and vehicle information. The information to update for a vehicle includes: the current location, the route to take, the destination, the time to have the next status change, the current status, and the next proposed status. All the information must be updated at each step. Each vehicle in the study network is treated as a moving node. If the position of a vehicle changes, the program updates the shortest path between each pair of nodes simultaneously. The information for an incident to update includes: the current status of the incident, and the required response time.
4. MODEL TESTING

4.1. Computation Time

The computational time is a major issue in this model to be applicable in real-time situation, so the computational efficiency should be examined. CPLEX is selected as a tool to solve the mathematical programming.

4 sample networks are created with sizes from 30 nodes to 200 nodes (Table 2). Number of emergency vehicles is about 1/6 of the number of nodes. Nodes are generated with 2-dimensional coordinates \((x, y)\). Each node is connected to nearby nodes by straight lines. Every node has about 4 links that are connected to it on the average. Incidents are generated randomly with some geographical distribution. The current location and destination of each vehicle is designated according to these incidents. For each network 5 tests are done. Different incidents and vehicles status are generated for each test.

For a network with 30 nodes, the average computational time is about 0.01 second, whereas the time is 0.17 second for a 200-node network. This indicates that the computation time increases almost linearly with the increase in the number of nodes in the tested range. This computation time is efficient enough for implementation in this research.

4.2. Parametric Sensitivity Analysis

Three sample networks are tested on reassignment condition threshold. Changing \(\tau\) from 0 to 20 minutes, the number of reassignments is decreasing gradually and finally becomes 0 as shown in Figure 4. When \(\tau \geq 10\) minutes, no reassignment is observed in these solutions.

Weights of response time \(a_i (i = 1, 2, ..., 5)\) are a set of important parameters that could impact the solution of mathematical programming. The weight of response time for incidents with \(i^{th}\) priority is \(a_i\). The formulation gives higher value of \(a_i\) to the incident with higher priority so that those incidents could be served earlier if possible.

The ratio of weights, or the relative weights of response time is defined as:

\[
r_{ij} = \frac{a_i}{a_j}
\]

The ratio of weights of response time is changed in 5 test scenarios. Test 1 gives equal weights to all types of incidents. Test 5 gives weights with the greatest differences to various types of incidents.

These 5 scenarios are tested in 2 sample networks with about 60 nodes and 12 vehicles. The average response times for incidents with different priorities are plotted in Figure 5. If an incident with higher priority is given a higher relative weight, the average response time for incidents with higher priorities is less than the average response time for incidents with lower priorities. In test 1, all incidents are given equal weights, so the average response times for all priority are approximately the same. In test 3, the average response time for incidents with 1st priority is 6.3 minutes whereas the average response time for incidents with the 5th priority is 8.8 minutes.

With the increase of ratios, the difference of average response time increase for example, in the test 2, difference of response time between incidents with 1st priority and the ones with the
5th priority is 1.2 minutes. The difference is 2.1 minutes in test 3, 4.5 minutes in test 4, and 4.6 min in test 5.

For test 5, the average response times before and after mathematical optimization are summarized in Figure 6. The response times before optimization are higher than those after optimization except for the incidents with the 5th priority.

5. CONCLUSIONS AND FUTURE RESEARCH

This study concentrated on developing a dynamic dispatch strategy and a simulation model to test the strategy. An integer programming formulation was proposed for developing the real-time dispatching strategy. The formulation utilizes dynamic shortest paths in determining the routes for vehicles.

A simulation model, which uses the formulation above as decision module, was also developed to demonstrate how the formulation works under real-time traffic conditions. Proper methods for travel time prediction and dynamic shortest path are selected upon full review of the state-of-art. A moving node method is created to track the location of emergency vehicles.

Although the simulation model presented in this paper is a prototype for real-time emergency vehicle dispatching, compared with traditional models, this new model has shown advantage in the following aspects when applied to real-time EMS vehicle dispatching,

- Real-time traffic information and dynamic shortest paths are used in this new emergency vehicles dispatching model. Traditional models use historical and static travel times to assist dispatch decision. The new model is advanced in utilizing the real-time information and it could improve the performance greatly especially when there is significant traffic congestion in the road networks.
- Flexible assignment strategy and system-wide mathematical optimization are employed in this model. Traditional models use queuing method and do not allow en route diversion. This model ensures that the EMS system is always working efficiently. The model shows advantages in that when severe incidents happen, the system can handle them in a more timely fashion and reduce important response times.

Future research can concentrate on developing better and more realistic model formulations that incorporate some of the real-world characteristics that may have been ignored in the proposed model. It can also concentrate on developing new and improved algorithms for solving these models and comparing the performance of the solution algorithms.
REFERENCES


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NOTATION
## TABLE 1
Possibilities of Next Dispatch Command

<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
<th>Possibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Waiting for command at home station</td>
<td>Leave for a destination on a specific route; Keep the “idle” status;</td>
</tr>
<tr>
<td>2</td>
<td>Moving to an incident point</td>
<td>Continue driving to the previous destination through the same route;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continue driving to the previous destination on a different route;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Change to a new destination;</td>
</tr>
<tr>
<td>3</td>
<td>Staying on the scene to treat an incident</td>
<td>Stay at the same point.</td>
</tr>
<tr>
<td>4</td>
<td>Transporting patient to a hospital</td>
<td>Go to the same hospital;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Go to the same hospital on another route;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Go to a different hospital.</td>
</tr>
<tr>
<td>5</td>
<td>Staying at hospital</td>
<td>Keep staying at hospital</td>
</tr>
<tr>
<td>6</td>
<td>Moving back to home station</td>
<td>Go back to home station on the same rout;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Go back to home station on a different rout;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Go to an accident spot.</td>
</tr>
<tr>
<td>Sample Network</td>
<td>Number of Nodes</td>
<td>Number of EMS Vehicles</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>
FIGURE 1
The Framework of Real-Time EMS Dispatching System
FIGURE 2
Methods of Tracking EMS Vehicles

Static Method

Dynamic Method

Moving Node
FIGURE 3
An Example of Reassignment

Vehicle 1  

Vehicle 2
FIGURE 4
Number of Reassignments Versus Reassignment Conditions Threshold $\tau$
FIGURE 5
Average Response Time with Various Weight Scenarios

![Graph showing Average Response Time with Various Weight Scenarios]

- Test 1
- Test 2
- Test 3
- Test 4
- Test 5

Incident Priority

Average Response Time (min)
FIGURE 6
Response Time Before and After Optimization