A Learning Real-Time Routing System for Emergency Vehicles

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***Abstract*-This paper describes a learning routing system designed to ease the movement of emergency vehicles through a network of congested streets. Real-time capabilities of the routing system are given by the use of GPS equipment installed aboard of every emergency vehicle. The same type of equipment is used to control the state of traffic lights and to collect real-time data on the current traffic volume. The actual routing algorithm is part of the A* class and reaches decisions with the help of a neural network that estimates the expected time of arrival of every feasible route the emergency vehicles might follow. Real-time traffic data is used to train the neural network and to help the routing algorithm work faster. This not only reduces the response time but it also increases the safety of the emergency vehicles.**

I. INTRODUCTION

This paper describes a joint research initiative of ESEO Group - Graduate School of Engineering, University of Angers and of the Technical University of Cluj-Napoca. The element that led to this initiative has been generated by the challenges faced by many emergency services in their attempt to improve the quality of their services. This is a challenging undertaking indeed not only because public expectations have become ever more demanding but also because traffic volume has increased significantly in the past few years.

The latter of the two factors is particularly important in the rapid developing cities where traffic systems can barely cope with the large number of cars that are on the move every day. One solution to the problem would be to make those cities more "car-friendly", that is to build new roads or to enlarge the existing ones. From a long term perspective this seems to be the best solution to the problem but in many cases such an initiative is not feasible because either local authorities do not have the necessary funds or they have to respond in a short period of time.

A case that clearly documents the need for a system similar to the one described in this paper is represented by the ambulance service in the city of Bucharest [9]. Ever since 1989 this particular services has been confronted with a severe lack of resources that has driven down the number of vehicles and qualified personnel. In 1996 however, the ambulance service benefited of an investment that installed an ITC system used to coordinate the entire dispatching process. Consequently, the quality of the service improved until 2002 when an increase of 6 minutes has been observed in the time required to allocate a vehicle to an emergency call. The main causes for such an evolution of the performance criteria were found to be: the increasing number of cars on the streets of Bucharest and the shortage of resources experienced by the ambulance service.

Another criterion that needed improvement in this case was the time to reach the emergency site. In 2005 the average dispatch time to a life threatening call was approximately 18 minutes [9]. This value is more than double to the one set by the UK government through the national performance standard that states that 75% of the immediately life threatening calls should be reached within 8 minutes (Reference [6] and [14]).

Generally, improvement in the arrival times could be accomplished through extensive and intensive measures. The first category would ask for new stations to be built in order to reduce the area covered by ambulances of a particular station. Although such an approach may lead to significant cuts in the response time it is not always implemented because of the high costs it assumes. Therefore, intensive measures are considered, more often than not, in order to facilitate the movement of ambulances and other emergency vehicles.

An increased traffic volume does not only increase the arrival times but it also increases the chances for emergency vehicles to become involved in accidents. A study performed in the mid '80 in the state of New York revealed that most accidents that involved ambulances occurred in intersections that had traffic lights installed [8]. Such events often resulted in serious injury or death and were explained through two main facts. Firstly, the light on the emergency vehicles could not attract attention because it is often obscured at intersections, and secondly, since the siren is also non-directional, it may bounce off buildings and trees, making it confusing for other motorists to pinpoint the vehicle's location [8].

The issue pointed out in the previous paragraph is actually the second problem dealt with in this paper. It will be referred to as the safety problem, while the one described earlier, would be known as the flow problem. Although quite different at a first glance the two issues could be considered together because they are generated by the same component of a traffic system: the traffic lights at an intersection.

Generally, traffic lights do delay every vehicle that passes through an intersection and thus influences the arrival times at the site of an emergency call. They are also those places where dangerous accidents do take place because emergency vehicles might have to run through red lights.

The system presented here aims to deal with the two problems concurrently and relies on a proper control of the traffic lights in order to reduce delays and prevent collisions. The

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quality improvement in the activity of an emergency service would be ensured through an approach that relies on traffic light systems that could differentiate between the various types of participants in the traffic and ease the movement through the city of those with a higher priority.

II. Related Work

The main objective of the work presented in this paper is to help emergency vehicles reach faster the site of a call. This could be formulated in terms of the graph theory as the "search for the route that minimizes the traveling time between two points of a street network".

Since the network of streets could easily be modeled with the help of a directed graph, the topic of this paper should be regarded as part of the general class of problems known in the literature as the Vehicle Routing Problems (VRP). Based on the amount of information that it is known before a vehicle begins its movement, there are two subclasses of problems dealt with in the literature: static and dynamic. In the static case, all data are known before the routes are constructed and do not changes afterwards, while in the dynamic case, vehicles are forced to react to events that occur in real time, such as new service requests, accidents or unexpected delays.

A topic that deals with emergency services does not fulfill all requirements of the previous taxonomy. The position of the emergency call does not change in time but emergency vehicles may have to change their route should the traffic conditions require such an action. The problem under study has been kept within the static VRP class with the help of two assumptions. The first one states that the probability of occurrence of an event that requires a route change is low. The second one assumes that the module that helps operators make routing decisions has enough information on the traffic to eliminate the need for route changes later on.

The topic of the paper could be more accurately classified if one takes into account the uncertainty that affects most of the events that define the activity of a traffic system. Queue lengths and vehicle delays are determined by the number of vehicles that are on the move and their speeds. These elements could be regulated with the help of the traffic lights but it is difficult to consider them as "fully controlled" or deterministic. Consequently, the work presented here is regarded as a stochastic variant of the static VRP.

Routing problems from the static class have already been studied for a long time so that nowadays they are well understood. Most of the VRP solutions, of interest for this paper, have a similar logic that arises from the work of a Dutch scientist, namely Edsger Dijkstra [5]. The case of emergency vehicles narrows down the class of algorithms to those that can find the shortest path from a given initial node to one goal node.

Such a task is widely solved today with the A* algorithm that was first described in 1968 by Peter Hart, Nils Nilsson, and Bertram Raphael [10]. A* works better than the original algorithm developed by Dijkstra for the routing problem at hand because it uses a distance-plus-cost heuristic function to determine the order in which the search visits the nodes in the graph associated to the street network.

Apart from its operational role the algorithm has an important role in placing this paper in the taxonomy of routing problems because it represents the single most important element through which this paper relates itself to the body of knowledge of static VRP.

The work presented here differentiates from most of the contributions to the static VRP because it is among the few that considers emergency vehicles as a special category of traffic participants and thus takes action in helping those vehicles reach their destination faster and safer.

Since traffic lights do hold a key role in the functions of the proposed system our work is related to several initiatives from the dynamic VRP area. For example, Reference [1] demonstrates that the minimum time problem in street networks with periodic traffic lights can be solved efficiently while Reference [12] addresses the impact of random travel times on the stochastic routing problem. Further more, Reference [18] describes an incident management system in which traffic lights are used to avoid traffic jams when accidents occur. The issue of real-time data is also presented in Reference [26], but in this case the authors focus on a traffic information system that would advise travelers on the best route for their journey.

Other related contributions that refer to the more technical aspects of traffic control could be found in References [7], [23] and [24]. These sources describe the features of several urban control systems that implement the concept of adaptive traffic control. Here too traffic lights are used to respond to the current traffic volumes but still they are not capable to meet the special needs of an emergency service.

III. Previous Work

The routing system presented in this paper collects the necessary real-time traffic information with the help of a system that has a structure similar to the one depicted in Fig. 1. Its infrastructure has been completed in a previuos phase of the project that has been completed in September 2007. More details concerning the communication process between system's components could be found in [25].

The data collection process has been built around a telemetry unit called RTCU-MX2i Professional [13]. Such a unit is capable of determining the geographic coordinates of its position

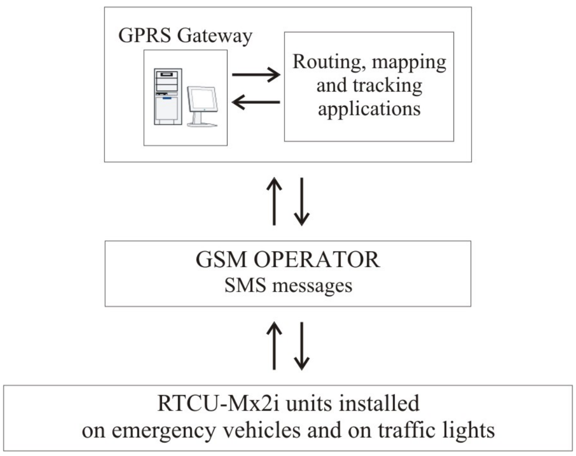

Figure 1. The general structure of the GPS routing system

and to acquire other data in digital or analog format. Furthermore, the unit has transmitting and receiving capabilities in the form of SMS messages.

Development of the "infrastructure" meant the implementation of three applications: the one that registers in a database the position of vehicles and other data transmitted by RTCU units, the mapping application and the one that implements the control of the traffic lights. From a routing point of view several new features had to be added to the infrastructure among which the most important were: the capability to determine the minimum time route to the site of the call and the capability to evaluate traffic volumes.

IV. The Proposed Routing System

The system described in this section achieves its goals not only through a routing algorithm but also with the help of the traffic lights that are dynamically controlled when emergency vehicles approach an intersection.

A. Determining the Moment when to Block the Intersection

In their way towards the site of a call emergency vehicles may have to pass through intersections. As they do, the risk of accidents is increasing especially when emergency vehicles may have to run through a red light. Depending on traffic volumes and on the intersection's layout the delay experienced by emergency vehicles may vary from a few seconds to a value that amounts to an important proportion of the arrival time.

To diminish or to eliminate such delays all together the proposed routing system would block the entry of all regular vehicles in an intersection to allow emergency vehicles to follow a path similar to the one illustrated in Fig. 2. There it can be seen that as it approaches an intersection the emergency vehicle is actually using the lane dedicated for the vehicles traveling in the opposite direction. In fact this kind of behavior could already be observed on a daily basis, but the safety of such of a manoeuvre is not high as other cars may enter the intersection and collide with the emergency vehicle.

To help emergency vehicles pass faster and safer through intersections all traffic lights will turn red as soon as the emergency vehicle is at a distance from the intersection that is smaller than $D_C(t)+Q_i(t)$. As it can be seen in Fig. 2, $Q_i(t)$ represents the length of the queue on lane ①, given by the number of vehicles that were traveling on the same lane as the emergency vehicle and could not pass through the intersection.

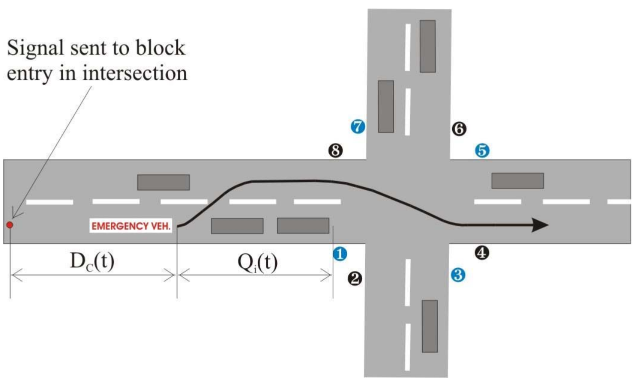

Figure 2. The expected path of emergency vehicles in intersections

The other element that determines the moment when entry into the intersection should be blocked, $D_C(t)$, represents the distance between the end of the queue and the point at which the emergency vehicle should block the movement of the regular vehicles. The safety of the emergency vehicle is ensured if the time in which the emergency vehicle covers the $D_C(t)$ is larger than the time needed by a regular vehicle to pass by the end of the queue formed on the lane on which the emergency vehicle is approaching the intersection. Using the notations introduced in Fig. 2, the constraint could be formulated as:

$$D_C(t) \geq \frac{v_{ev}}{v_{rv}} \times \left(E[Q_i(t)] + D_{\text{int}}\right) \tag{1}$$

where, v_{ev} represents the average speed of the emergency vehicle, v_{rv} - the average speed of the regular vehicle, $E[Q_i(t)]$ - the expected value of $Q_i(t)$ and D_{int} - the distance traveled by the regular vehicle through the intersection up to the beginning of the destination lane.

Several traffic flow models could be used to determine the expected maximum value of $Q_i(t)$. A good reference on these models could be found in [21]. The one that approximates the best the expected number of waiting vehicles at the beginning of the red phase is known as the Newell's formula [17]. The formula, however, is rather complex so $E[Q_i(t)]$ has been approximated through a more simple expression.

During the red phase of a traffic light, the number of vehicles that accumulate in the queue is given by:

$$Q_i(t) = c_l \cdot \int_0^t \lambda(t)\,dt \tag{2}$$

and, its expected value could be approximated by:

$$E[Q_i(t)] \approx 1.2 \cdot c_l \cdot (c - g) \cdot \lambda \tag{3}$$

where, c_l represents the average length of a car, c – the duration of a cycle, g – the duration of the green phase and λ – the average arrival flow rate associated with the traffic in the previous cycle.

The values of λ are constantly updated by the RTCU telemetry units that have the capability to collect real-time traffic data. In this way their values are close to the real arrival rates that led to the queue observed by the emergency vehicle. The value of $E[Q_i(t)]$ has been increased by 20% to ensure a safe passage of the emergency vehicles. The choice has been made despite the fact that this decision also increases the delay for all other regular vehicles.

In (1) one should pay attention to the selection of the "regular vehicle" that will provide the necessary data (speed and distance traveled). For example, in Fig. 2, the vehicle traveling in the opposite direction to the emergency vehicle could have come from lane ③, ⑤ or ⑦. Assuming that there are no special problems with the left and right turns it is expected that vehicles traveling on lane ③ would need the longest time to pass through the intersection and therefore their data should be considered in (1). However this may not be the case for every intersection and thus the lane that will provide the values for v_{ev} and D_{int} should be selected through direct observations.

B. Acquisition of Real-Time Traffic Data

This capability of the routing system is ensured by the features of the RTCU MX2i unit. The professional version of the telemetry unit has 5 digital inputs, two analog inputs, a temperature sensor and with the help of a VGA camera could take colour pictures in standard JPEG format. All these features ensure that performance of the unit is limited only by the capabilities of the sensors and make it one of the most powerful tools in real-time data acquisition. It can collect data about traffic volumes on each lane and weather conditions, to name just those elements that are of most interest from a traffic control point of view.

C. The Structure of the Routing System

Generally, routing problems can be modeled with the help of a directed graph G = (N, A), where N is a set of nodes, representing the intersections of a street network while A comprises of the set of arcs associated with that particular street network. To each arc (i, j) in A one could assign a nonnegative travel time d_{ij} and a travel cost c_{ij} with the following meaning. If "t" is a feasible leaving time from node "i" along the arc (i, j), then t $+d_{ij}$ is the arrival time at node "j". The second element mentioned above, c_{ij}, represents the cost of traveling from node "i" to "j" through arc (i, j) starting at time t.

The particular case studied in this paper differs from the traditional routing problems through the need to take into account an additional waiting cost that is associated with node "i". Thus, a new variable $w_i(t)$ should be added to the above model to consider right-turns, left-turns or straight-through movements in an intersection. $w_i(t)$ values are different depending on the route of the vehicle. However, they do not change the logic in which the solution to the routing problem is found despite the fact that they may have an impact on the actual route followed by the emergency vehicles.

A* is a graph-searching algorithms that combines the logic of the Dijkstra's algorithm with a heuristic called Best-First-Search. The latter of the two holds an important role in the logic of A* because it guides the search process towards the nodes that are close to the goal. The "cooperation" of the two algorithms is expressed by the f(n) function that actually guides the search process.

$$f(n) = g(n) + h(n) \tag{4}$$

It is formed of two terms that represent the cost of the path from the starting point to any node "n" - g(n), and the heuristic estimated cost from node "n" to the goal - h(n). A* balances the two as it moves from the starting point to the goal. Each time through the main loop, A* examines the node "n" that has the lowest f(n) value.

The use of A* in solving the routing problem for emergency vehicles differs from the traditional approach in two ways. Firstly, for reasons outlined above, one needs to add the value of $w_i(t)$ to h(n) in order to take into account the time a vehicle would need to cross the intersection. The adjustment of the h(n) is necessary since $w_i(t)$ values could be significant from an emergency point of view. The second argument that leads to a specific use in this paper of the A* algorithm is the fact that g(n) values are not always known because in fact d_{ij} values are not known. This could be the case particularly immediately after the introduction of such a system when one can only estimate the values of d_{ij}. The estimation process could be made very simple as the street lengths and the average speed of the emergency vehicles are more or less known. The estimates obtained in this way could be only seconds adrift from the real d_{ij} values, so it may seem as if there is no point in spending time and effort in finding more accurate values. This kind of logic is not appropriate for emergency services because in these cases minutes and even seconds could make the difference between life and death.

An answer to the problem of determining accurate values for the traveling times on each street is illustrated in Fig. 3. There it can be seen that the actual routing module is requesting data from a neural network while it searches for the fastest path towards the site of the emergency call. In this system the neural network could be thought of as a special type of database that contains real time traffic data recorded by the telemetry units aboard the emergency vehicles. Every trip made by an ambulance, for example, would add new d_{ij} data to the neural network. A simple database however could not fulfill the requirements of an accurate routing system because each d_{ij} data is observed under specific traffic conditions and therefore a particular value is not representative for all traffic conditions. The routing problem in the case of the emergency vehicles asks for a database that is capable to provide data even when that data has not yet been registered. This type of behavior can only be found in neural networks due to their internal structure that once trained can recognize members of a set even if those members have not been encountered before. Adopting such an approach assumes that the neural network will be in a permanent state of learning or training. Of course, in the early stages of its training the network might have to satisfy requests for data it cannot recognize. The default option in such a case would be to calculate the traveling times as the ratio between the length of the street and the vehicle's average speed.

D. The Learning Capability of the Routing Algorithm

The motivation for a learning routing algorithm is generated by the need to decrease to the minimum the traveling time to the site of an emergency call. It was also determined by the observation that drivers do learn which are the fastest routes and in time they do not bother anymore to explore other alternatives.

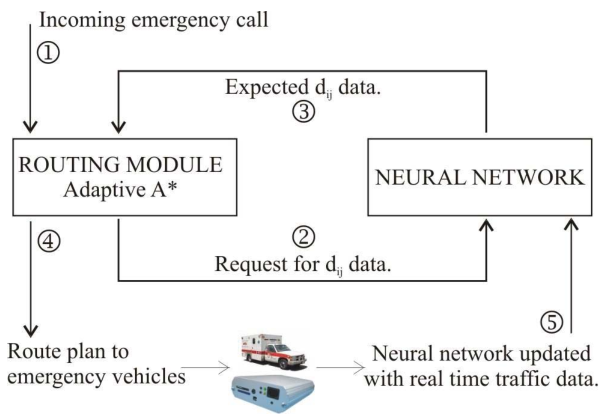

Figure 3. The general structure of the routing system

The map illustrated in Fig. 4 points out exactly this idea. If an ambulance is requested on the place indicated by the red mark and the ambulance is dispatched by one of the two central hospitals (Saint-Andre or Sainte-Blandine) then there are only four realistic possibilities to cross the river. This suggests that the use of A* could be improved if the journey of the emergency vehicle would be imagined as being formed of two segments determined by one of the crossings of the river.

The advantage generated by such an approach resides in the fact that the path between the hospital and a bridge could be determined apriori and thus, the size of the initial problem could be reduced. The role played in this example by the bridge should not be characterized only through the restrictions it imposes on paths in a street network. The bridge should rather be seen as a landmark, a reference point that can help decompose the initial routing problem and facilitate the learning process through which the fastest path is found. Consequently, bridges would not be the only candidates for landmarks in a learning routing algorithm. All major intersections could fulfill this role. An empirical way of finding these candidates would be to monitor the activity of the emergency services, a task that is greatly simplified by any tracking and mapping applications.

The last idea points out the second important role played by the telemetry units in designing a learning routing system, that is the identification of the reference points. The first one has been described earlier and it referred to the process through which the neural network acquired real-time traffic data (d_{ij}).

The use of reference points does raise questions with respect to the optimal character of the path proposed by the routing system as a significant number of alternative paths could be eliminated from the search process. To reduce to the minimum

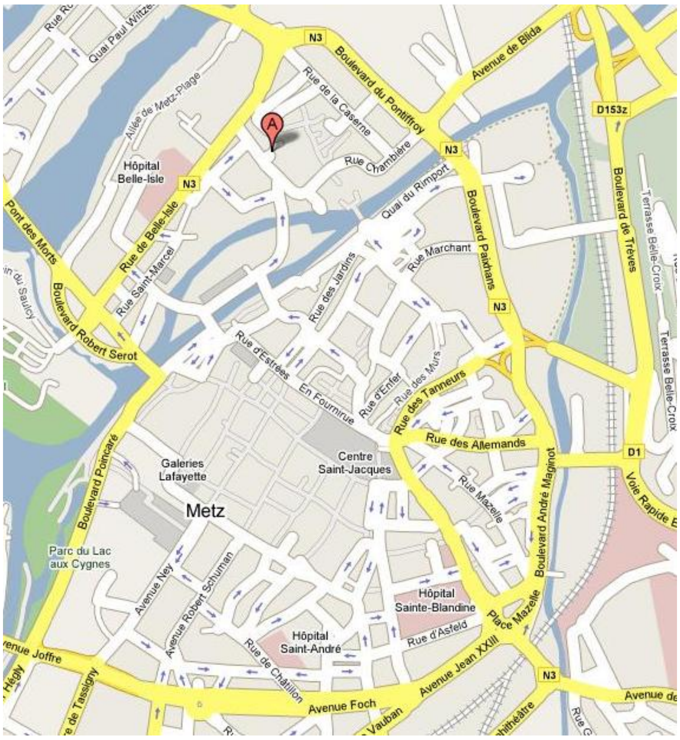

Figure 4. An example of a street plan that supports the idea of a learning routing algorithm

the risks of finding a "bad" solution the heuristic presented next has been designed to investigate a larger number of reference points than an A* based logic would consider.

E. *Pseudocode of the Learning Routing Algorithm*

The actual routing algorithm has been designed as formed of two procedures: one that finds the fastest path towards the goal node (LRA) and another that updates the information in the neural network (NNU) with the help of the real time data collected by the telemetry units installed aboard the emergency vehicles.

The routing problem is actually solved by the LRA but only with the help of critical data supplied by the NNU procedure.

LRA procedure

1. Determine set $S=\{i \mid i \in SRP, h(i) \leq h_g\}$,
   where SRP is the set of all reference points, h(i) the Euclidean distance between the reference point 'i" and the goal node "g" and h_g the distance between the origin and the goal node.
2. *if* (set S is null)
   then apply A*;
   else{
   - mark all nodes in S as not visited;
   - *while* (there are unvisited nodes in S) *do*{
     →find unmarked "i" in S for which f(i) is minimum – f(i)=g(i)+h(i) – where g(i) is the travel time on the fastest path from origin to node "i";
     →apply A* to find the fastest path from node "i" to the goal node "g";
     →mark node "i" as visited;
     →update the optimum path to the goal node;
     }
   }

NNU procedure

1. use LRA to determine the fastest path to the site of the emergency call;
2. use GPS data to determine d_{ij} traveling times on each street that was part of the route of the emergency vehicle;
3. update g(i) values for all reference points on the path of the emergency vehicle.

F. *Performance of the Learning Routing Algorithm*

The algorithm proposed in this paper has been designed around the A* logic, so its performance is roughly "similar" to that of the A* algorithm. The same is true for its problems as well. The time in which A* finds a solution depends on the number of nodes generated in the search process. This number is polynomial only if the error of the heuristic function does not grow faster than the logarithm of the true distance from a particular node to the goal node [22].

More problematic than its time complexity is A*'s memory usage. In the worst case, it must also remember an exponential number of nodes. To cope with these problems the proposed algorithm takes advantage of a decomposition procedure that can reduce the size of the search space, and in doing so, decreases the time and the memory space required to find the solution. The advantage of such an approach arises from the fact that it is better to deal with several smaller problems especially when the complexity of the algorithm is exponential. The running time of the proposed LRA is decreased further by a limit set on the number of reference points that are considered in the search process. The heuristic investigates only those reference points that are located in an area of radius equal to the Euclidean distance between the origin and the goal node.

V. Concluding Remarks

The system described in this paper has been designed to help emergency vehicles move faster through the street network of a congested city. It accomplishes its role by controlling the traffic lights and by finding a path that would take the vehicle in the shortest time possible to the site of the emergency call. The first part of this functionality is based on the assumption that emergency vehicles would pass through intersection faster and safer if the other vehicles are prevented from entering the intersection. Consequently, traffic lights are turned red with the help of a complex telemetry unit so that the emergency vehicles could even use the lane for the vehicles travelling in the opposite direction. The added value of the proposed system is further enhanced by a routing algorithm that guides the vehicles through the street network. As all algorithms of its class LRA needs accurate data on travel times on each particular street on the path to the emergency site. Two entities work together to provide the LRA with the required data. Telemetry units installed aboard the emergency vehicles that record real-time travelling data and a neural network that provides an estimate of the travelling times depending on traffic conditions.

The routing algorithm implemented by the proposed system inherits all the good features of an A* type of algorithm and it is supposed to work better even when the search process has an exponential complexity. This has been achieved with the help of a grid of reference points through which emergency vehicles pass frequently. The grid actually decomposes the initial routing problem into a set of similar but smaller problems that are easily dealt with. As a consequence, the routing system is expected to work faster than the original A* algorithm and will ensure a higher degree of security for emergency vehicles as they pass through intersections.

The selection of the reference points is still an issue under consideration because the problem has not yet been modeled analytically and therefore the solution relies entirely on decisions made on data resulted from analyses of the routes followed by the emergency vehicles.

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