Dynamic Path Planning and Traffic Light Coordination for Emergency Vehicle Routing

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I. INTRODUCTION

Expeditious movement of emergency vehicles to and from the scene of an accident can greatly improve the probability that lives will be saved. There are some potential barriers to this expedient movement that range from synchronized operation of traffic lights to the traffic conditions in the current and nearby intersections. Since traffic lights can control traffic flow at intersections, they can guide the flow of traffic to favor movement in the direction that best suits the emergency vehicle. This factor has been a key component for preventing traffic-related delays for emergency vehicles.

Since the 1960s, as different technologies were introduced, the approaches taken to solve the problem of effective emergency vehicle routing accordingly evolved. Initial strategies of using noisy sirens were deemed insufficient to clear traffic that blocked the path of an emergency vehicle. Thus, traffic lights were coordinated to move traffic in directions that would clear congestion on the route of the emergency vehicle. The main idea is to communicate the presence of the emergency vehicle to the relevant traffic lights and notify the traffic light of the emergency vehicle’s position and direction of travel. Detectors for strobe lights and sirens were attached to traffic lights to enable them to recognize the emergency vehicles. However, these approaches required clear line of sight which was difficult to maintain in bad weather conditions, near curves, or most importantly, when obstacles prevented this line-of-sight detection.

To address these difficulties, radio and microwave signal transceivers were deployed to improve the communication between the emergency vehicles and the traffic lights [2][3][4][5][6][7]. When Differential Global Positioning System (D)GPS technology emerged it was possible to track the position of emergency vehicles more accurately and indicate the arrival of an emergency vehicle at an intersection much earlier [8][9]. A later improvement that was added to emergency vehicle routing to further reduce its travel time was static path planning, where a variety of algorithms were employed to choose the fastest path to the destination based on the congestion information available at the time of planning the path. This approach adopted by Kim and Kwon used Dijkstra’s algorithm for static path planning for the emergency vehicle and dynamically pre-empts the traffic lights as the vehicle travels along its route [9]. Their solution provides an online route selection module that when queried checks the current traffic conditions and statically recalculates the least cost path from the vehicle’s location to the goal.

Although path planning is an enhancement of previous approaches in that it views the route in its entirety and not just the local impediments, path planning approaches have adopted a static perspective on route planning. This ignores the possibility that costs are constantly changing because the level of congestion keeps changing over time. While Kim and Kwon [9] provide an online route selection module, not until a replanning request is made that current changes in traffic conditions is a better approach.

Accordingly, one possible development that can be built on the previous approaches to further improve the emergency vehicle’s travel time is to efficiently and dynamically plan the emergency vehicle’s route. Even though static path planning has improved travel time for the emergency vehicle, when the traffic conditions on the roads change, the static path fails to take the changed conditions into considerations. Thus, performing path planning dynamically depending on the updated traffic conditions is a better approach.

This paper presents a solution that combines dynamic path planning with preemption. The dynamic path planning uses D* Lite, an informed search algorithm that can efficiently and optimally plan and replan according to changing costs in the traffic network. The cost of a given route translates to the travel time of that route since the main goal is to reduce the emergency vehicle’s delay. For a chosen route, a preemption strategy is used to select a signal phase that reduces the emergency vehicle's delay, and when possible, maximizes flow for other vehicles approaching the intersection. We evaluate our work at two levels. First, an initial evaluation is conducted using the graph version of D*Lite we have implemented. Extra costs are assigned to nodes or intersections when preemption is not in effect, and extra costs are assigned to edges to indicate the congestion effect. Our preliminary results indicate how dynamic path planning combined with preemption outperforms static path planning especially during the presence of congestion in the network. Our second evaluation is based on scenarios being developed using a microscopic traffic simulator; VISSIM.
II. PROPOSED SOLUTION

A. Assumptions and Challenges

Before getting into the details of the solution, there are some assumptions on which the proposed solution builds. First, traffic lights are controlled by a central server. This is necessary for having an overall view of the entire traffic network. Second, we assume constant connectivity between the emergency vehicle and this central server. This can be done through many technologies which in cases might be expensive but worth deploying for emergencies. Third, a congestion detection system is assumed to be there to measure the congestion level on the roads of the network. Fourth, the emergency vehicle needs to have a GPS tracking system so that it can determine its current location and send this information back to the server. Fifth, a traffic model that identifies traffic flow patterns at intersections is needed to give estimates on which path planning and preemption depend.

B. System Architecture

The proposed solution consists of two main parts, dynamic path planning and preemption. As shown in Figure 1, the destination and current location of the emergency vehicle is determined using data from the GPS tracking system. We then model the traffic network between the source and destination as a graph where nodes represent intersections and edges represent the roads in between. Afterwards, costs are assigned to edges. Since the goal of the whole solution is to reduce the emergency vehicle’s travel time, cost of a particular edge is translated to time needed to travel along that edge. It is set to be the estimated travel time of the edge including time to traverse it and time to ease congestion along it. Once costs are assigned to edges, the graph is ready to be given as an input to the dynamic path planning algorithm, i.e. D* Lite. The algorithm keeps receiving updates about the current location of the emergency vehicle using GPS data and the current costs of the edges using the assumed congestion detection system, and accordingly outputs the best route available at any point in time. After identifying a path, the preemption process can start early depending on the time the vehicle is expected to arrive at intersections along that route. Finally, for every intersection affected by the preemption process, a recovery phase is applied to the traffic lights to restore back their normal operation once the emergency vehicle passes through.

1) Dynamic path planning: D* Lite is an informed or heuristic search algorithm first invented by Keonig and Likhachey in 2002 and since then has been used in different applications for dynamic path planning. It can be customized for a specific domain using heuristic. This heuristic makes it specific to the problem and guides the search by giving estimates about the costs between a current state and the goal. It is an enhancement of another informed search algorithm called A*, specifically Lifelong Planning A*. Most of D* Lite properties are inherited from Lifelong Planning A*. However, unlike Lifelong Planning A* that does forward search, D* Lite does backward search. This property makes repairing the current plan easier in D* Lite because goal stays fixed and start node keeps moving around [11]. D* Lite is a simpler version of D*.

We believe D* Lite to be a suitable choice for applying dynamic path planning to emergency vehicle routing for a number of reasons. First, it is provably complete, optimal, and can handle dynamic cost changes [10]. This feature is significant for vehicle path planning based on traffic conditions, such as congestion level, that can suddenly change at anytime. Second, D* Lite implements fast replanning because it does not plan from scratch but rather fixes the current plan considering those edges affected with the changes and only the ones that matter to the least cost path. During emergencies, this fast replanning would save the emergency vehicle unnecessary time spent planning from scratch. Third, D* Lite makes no assumptions about how the costs of the edges are changing. This is necessary for accurate routing of emergency vehicles because the cost or travel time of the roads can increase dramatically due to sudden incidents, like car accidents. Thus, we should not assume anything about costs in this case.

To apply D* Lite to emergency vehicle path planning, we implemented a graph version of the algorithm which was needed to incorporate the intersections, the roads and their associated costs. We modelled the intersections as Node object and the links are defined as Edge object.

Since, D* Lite uses admissible heuristic, the heuristic used to estimate the least travel time link or road in the network or graph is the link distance divided by the Vehicle’s maximum speed. This heuristic is admissible, i.e. does not overestimate cost, because it estimates the travel time based only on distance and the maximum speed of the vehicle. While there
are other factors, like congestion, that might affect travel time of a link or road, these factors do not always happen to exist. Thus, adding them to the heuristic would be an overestimation and would make the heuristic inadmissible.

![Figure 2: Defining traffic signal phases][9]

2) Signal preemption: Signal preemption means ending the current phase the traffic lights are at and switching to another phase (or extending the current one) to allow fast and safe travel of the emergency vehicle. We address two main questions while working on pre-emption. The first question is how preemption is done? The second is when should preemption start?

**How is preemption done?**

Deciding how preemption is done mainly depends on satisfying the expedient movement of an emergency vehicle and then, if possible, maximizing traffic flow at the intersection. Maximizing the flow on the other approaches, i.e. other than the one the emergency vehicle is coming from, of the intersection is not possible unless doing this does not affect the emergency vehicle’s delay and safety. With this goal in mind, the traffic lights phase selection depends on the congestion level, the current phase of the traffic lights when preemption is triggered, and on the intersection approach from which and to which the vehicle is heading.

Figure 2 shows an example of traffic light phases that can be used to explain the phase selection algorithm. These phases were borrowed from the work by Kim and Kwon [9]. We build over their work and develop a different preemption plan. In this example, the possible destinations of a vehicle coming from any of the four sides of the intersection are indicated by numbers. A phase reflects the set of traffic lights, indicated by numbers, that have a green light at the intersection. As shown in Figure 2, the phases’ cycle starts with (4+7) which means that traffic lights 4 and 7 are green and every other traffic light at the intersection is red.

Now that the traffic lights phases are identified, it is important to consider how to control these phases to achieve the aforementioned preemption goal. This control depends on the level of congestion as we briefly show.

### Table 1: Traffic signal phases selected when level of congestion is high

<table>
<thead>
<tr>
<th>Vehicle Destination</th>
<th>The current signal phase when the emergency vehicle arrives at the intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7</td>
</tr>
<tr>
<td>South</td>
<td>4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7</td>
</tr>
<tr>
<td>East</td>
<td>4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7</td>
</tr>
<tr>
<td>West</td>
<td>4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7, 4+7</td>
</tr>
</tbody>
</table>

To begin with, if the level of congestion is high, then delay can be imposed onto the emergency vehicle’s route. Traffic, therefore, needs to be cleared around the emergency vehicle as much as possible. Given the current phase of the traffic lights and the emergency vehicle’s origin/destination, we built Table 1 to indicate the best phase to select to ensure a fast and safe travel of the emergency vehicle through the intersection. The rows represent the directions of the emergency vehicle at the intersection, while the columns describe which of the eight phases has the green lights on when the preemption is triggered. The results of the table can be summarized in that regardless of the current traffic light phase when the emergency vehicle arrives, and regardless of its destination on the intersection, all traffic lights on the destination it is coming from has to be green. This is reflected in the four phases: (4+7) if the vehicle is approaching the intersection from the North, (3+8) if it is coming from South, (2+5) if it is coming from West and (1+6) if it is coming from East. Doing this ensures that the emergency vehicle would get delayed by traffic on its route. The green coloured cells represent the case where the preemption is triggered when the right phase is on so we just extend the green light for the phase until the vehicle is through.

On the other hand, if the level of congestion is low then the emergency vehicle’s expedient movement is quite easy to achieve so traffic flow on other approaches of the intersection can be maximized as well. Thus, the phase selection criteria becomes as follows. If the current phase allows the vehicle to get through to its desired approach in the intersection, we extend the phase. Otherwise, we pick the phase that maximizes vehicle flow on the other sides of the intersection. Applying these criteria to the eight defined phases given the current phase when preemption is initiated and the desired origin/destination intersection approaches of the emergency vehicles, results in Table 2. An example to clarify the algorithm under low congestion conditions is when the vehicle is heading from North to South, i.e. second row in Table 2, on the intersection while the green signal phase is (3+8), i.e. third column.
Table 2: traffic signal phases selected when level of congestion is low

<table>
<thead>
<tr>
<th>Vehicle Direction</th>
<th>The current signal phase when the emergency vehicle arrives at the intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>4+7 3+7 4+8 3+8 4+9 3+9 4+10 3+10 4+11 3+11 4+12 3+12 4+13 3+13 4+14 3+14</td>
</tr>
<tr>
<td>South</td>
<td>4+7 4+8 4+9 4+10 4+11 4+12 4+13 4+14 4+15 4+16 4+17 4+18 4+19 4+20 4+21 4+22</td>
</tr>
<tr>
<td>East</td>
<td>4+7 4+8 4+9 4+10 4+11 4+12 4+13 4+14 4+15 4+16 4+17 4+18 4+19 4+20 4+21 4+22</td>
</tr>
<tr>
<td>West</td>
<td>4+7 4+8 4+9 4+10 4+11 4+12 4+13 4+14 4+15 4+16 4+17 4+18 4+19 4+20 4+21 4+22</td>
</tr>
</tbody>
</table>

Considering the phase choices available to get a vehicle from North to South on the intersection, there are two phases, (4+8) and (4+7). Since the level of congestion is low, emergency vehicle delay is not a concern in either case. However, delaying other traffic on the other sides of the intersection is a concern. Choosing (4+7) would allow vehicles coming from South and heading East or North to move through while choosing (4+8) would keep these vehicles waiting unnecessarily. Thus, the Table outputs (4+7) in this case. The rest of the blue colored cells are filled applying same analysis.

Comparing the two tables, the green cells are the cases on which they match. In other words, these are where high or low congestion make no difference in our phase selection decision. This result indicates that only one eighth of the times preemption phase selection is not affected by congestion while the most of the time congestion needs to be taken into consideration.

When should preemption start?

How early preemption should be triggered for a given intersection approach also differs depending on congestion level. The base case is when there is no congestion. In this case, the factors affecting how early preemption should occur are the time the vehicle is expected to arrive at the traffic light and the phase transition time, i.e. time needed to end the current traffic signal phase and switch to another one. A safety margin is also needed for ensuring no delay affects the vehicle’s travel time. If the vehicle is approaching intersection traffic light X and expected to be at the stop line of the traffic light at time τ and the transition time is Trans, then time to start preemption at X, or

\[ p_e = \tau - \text{Trans} - \text{safety margin} \]  

On the other hand, if congestion is introduced into the network, then preemption should start earlier considering the congestion effect on the vehicle’s travel time. For a given approach to an intersection, there are two possible delays that can affect the travel time of vehicles on that approach. This is based on a new Time dependent travel time estimation model developed by Linu and Ma [12]. First, the Signal delay which they define as the time spent at the traffic light due to red light. However, since preemption occurs before the vehicle is at the traffic light, this delay will not affect the emergency vehicle. Second, the queuing delay which they defined as the time needed to clear queue of vehicles between the vehicle and the traffic light stop line. This delay is very likely during congestion and it can affect the emergency vehicle’s travel time. Thus, taking this delay into account preemption at X now becomes:

\[ p_e = p_s + \text{Queuing Delay} \]

III. Evaluation

A. Preliminarily Evaluation

This evaluation is conducted using our D*Lite graph-based implementation where costs, other than distance, are assigned to edges for Queuing Delay due to congestion and costs are assigned to nodes for signal delay. Initial test cases were run where we used two graphs, as shown in Figure 3. One is simple with one decision point between the source, a, and the destination, d. The other graph is more complex where there are many routes that can be taken between the start, A, and destination M. The numbers on the edges indicate the length of the network roads in Kilometres. The emergency vehicle’s max speed is assumed to be 120 Km/hr. To test cost and intersection delay, when preemption is not done, a 3 minutes cost was assigned to nodes, or intersections, between the start and the destination. In cases where there is no congestion, queuing delay is assumed to be zero. When there is congestion an estimated cost, 7 minutes, is assigned to some edges in the network to indicate the queuing delay mounting at these edges. As a lower bound in terms of delay, preemption is assumed to be done perfectly leaving no congestion along the vehicle’s route.
Overall, as results indicate in Figure 4, dynamic path planning shows significant improvement over static path planning. The difference is more prominent in the complex graph scenario. When there is zero congestion, then static and dynamic path planning give the same travel time results as one would expect. However, when congestion occurs, a clear travel time improvement is observed with dynamic path planning. The most obvious difference in performance is in the complex case where there is no preemption and a lot of congestion. This preliminary result indicates that even in cities where doing preemption is not feasible, dynamic routing alone can make a big difference. When preemption is added a clear cut in travel time takes place in both dynamic and static routing but dynamic path planning saves more time because it preempts the least cost path.

B. VISSIM Evaluation

At this point we understand that our initial set of results abstract many details in a real traffic network. To further verify our results, we plan to test our solutions and algorithms over a more realistic environment using specialized simulators. The complementary set of results we plan to present in our final document will be conducted using a microscopic traffic simulator called VISSIM which we have been exploring. VISSIM has been developed in Germany by Planung Transport Verkehr (PTV) company. It simulates urban and highway traffic, including pedestrians, cyclists and motorized vehicles. It has been used to model different traffic engineering problems [13]. One major advantage of VISSIM over other existing traffic simulators is its flexible structure that allows continuous interaction between VISSIM’s main simulation module and an external module that controls every traffic light in the network [9]. Thus, for this research’s interest, the preemption algorithm can be separately coded into an external module that would continuously interact with VISSIM. VISSIM in turn gives simulated detector data to the external module.

At this point, we have developed an initial scenario of a Manhattan Grid network (zoomed in screenshots shown in Figure 5). This scenario sets the traffic lights to behave in the phases defined in Figure 2. Our remaining work, therefore, is primarily in evaluation; interfacing the preemption plan and implementing D* Lite within VISSIM.

REFERENCES