Route-based Dynamic Preemption of Traffic Signals for Emergency Vehicle Operations

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ABSTRACT

A route-based dynamic strategy is developed for efficient preemption of traffic signals for emergency vehicles in real time. The proposed method combines an on-line route selection module and a sequential dynamic preemption strategy, so that traffic queues at the intersections on a given emergency route can be cleared in advance for an emergency vehicle, while minimizing delay because of unnecessary preemption. The proposed strategy was simulated in a real traffic network using a microscopic simulation model, which was calibrated with the emergency vehicle travel time data collected from the sample network. The performance of the proposed dynamic preemption was compared with that of the existing intersection-by-intersection preemption strategy which was also modeled and simulated in this study. The simulation results clearly indicate substantial benefit of the proposed strategy over the existing method for the long and complicated routes in reducing the travel time of an emergency vehicle, while maintaining compatible network-wide traffic performance.

INTRODUCTION

Providing safe and fast driving environment for emergency vehicles, so that they can reach their destinations at the earliest possible time, is of critical importance in saving lives and reducing property loss. While substantial progress has been made in the areas of vehicle detection and communication technologies, current state-of-the-art in signal preemption in the U.S. has not reached the point where route-based signal clearance strategies can be automatically generated and implemented in real time. To be sure, most preemption systems developed to date operate on a
single-intersection basis and require local detection of an emergency vehicle to activate a signal preemption sequence at each intersection. Such a local detection-based, intersection-by-intersection clearance strategy results in inherent time-delay at intersections, since the signal preemption procedure can start only after an emergency vehicle is detected. Further, in a heavily congested network, e.g., during peak-periods or after athletic events, the requirements of local detection for activating signal preemption present substantial problems in clearing the intersections quickly enough for an emergency vehicle to pass them without stopping or reducing its speed.

This paper presents a route-based dynamic preemption approach, which combines an on-line route selection procedure and a dynamic sequential preemption method to provide the most efficient and safe route for an emergency vehicle under a given network and traffic conditions. The proposed strategy was evaluated at the University of Minnesota campus network in Minneapolis, Minnesota, using a microscopic network simulation model by comparing its performance with that of the existing intersection-by-intersection preemption method.

BACKGROUND

Existing signal preemption methods are in general classified into several categories depending on the technologies used for detecting emergency vehicles, i.e., optical, infrared light, acoustic, special types of loop detection, and GPS-based systems (1, 2). The optical systems, developed in the 1960’s and the most commonly used ones in the field, use a strobe-lamp on the vehicle and an optical sensor per approach to an intersection requiring a clear line-of-sight path between the vehicle and the intersection (3). The sound-based systems use the directional microphones installed at an intersection to detect the siren of vehicles approaching a given intersection, therefore, no special equipment is required for the emergency vehicles (4). In radio-based systems, the directional signal for preemption can be transmitted from a vehicle to an intersection via one-way radio. The GPS approach uses the satellite-based Global Positioning System and determines the signal preemption time depending on the position, speed, and travel direction of the emergency vehicle approaching an intersection. In a GPS-based system being operated in Peoria, Illinois, both an emergency vehicle and an intersection are equipped with a GPS receiver and a radio transceiver for two-way communication (5). In an ongoing study by the City of Los Angeles, the feasibility of using a special loop sensor with transponders for emergency vehicle preemption is being tested (6). The above preemption systems adopt the intersection-by-intersection clearance approach based on local detection, and the impacts of such preemption strategy on the signal coordination and corridor-wide travel times of normal vehicles was first studied by Bullock, et. al. (1), who developed and applied a hardware-in-loop simulation-based evaluation procedure for the Route 7 Virginia corridor. A more recent study by Bullock et. al. (2), who used three controllers in a hardware-in-loop simulation system, found out that the second and third preempts in a peak period had significant impacts on queuing and delay for normal vehicles on a given network.

As indicated above, while there has been substantial progress in developing local preemption technologies, very few research results on the route-based dynamic preemption have been found in the literature. In fact, the only route-based signal clearance research found from the literature was the Fast Emergency Vehicle Preemption System (FAST) developed by a group of Japanese researchers (7), while the detailed algorithm of FAST and its effectiveness over existing preemption strategies haven not been published. Developing a route-based dynamic preemption strategy that can provide an efficient and safe traveling environment for emergency vehicles with minimum disruption on network traffic is of critical importance in managing urban traffic. In this paper, a
route-based dynamic strategy for signal preemption is proposed and its effectiveness over the existing local-detection based method is evaluated.

ROUTE-BASED DYNAMIC SIGNAL PREEMPTION

Figure 1 shows the simplified structure of the route-based dynamic signal preemption strategy developed in this study. The network-monitoring module continuously collects traffic data from field detectors and quantifies travel cost of each link, i.e., a section of roadway between two intersections, by combining its length and current congestion level. When an emergency call is received at the control center and after the current location of an emergency vehicle (EV) available is identified, the route-selection module determines the quickest route between the current location of the EV and a given destination. In this research, the well-known Dijkstra’s algorithm (8) is adopted to find the optimal route that has the minimum travel cost under current traffic conditions for a given origin-destination pair. Alternatively, an emergency-vehicle operator, e.g., police person, can determine an emergency route based on his/her preference and local knowledge. Once an emergency route is selected, the dynamic preemption module starts the preemption of the signals on the emergency route sequentially considering the location of the EV and the state of signal phase for each intersection. As soon as an EV clears an intersection, the signal recovery module, starts the process to recover the original offset and cycle length of that intersection by adjusting the ‘Walk’ time interval in each phase. The proposed strategy assumes that the two-way communication between an emergency vehicle and the control center is available and the location of the emergency vehicle can be detected at the control center with a GPS or loop-transponder based systems. Further, the preemption sequence at each intersection can be activated at the control center. Therefore, the focus of this study is to evaluate the potential effectiveness of a route-based dynamic preemption method over existing intersection-by-intersection preemption strategies. The rest of this section describes the major features of each module.

Quantification of Link Travel Cost through Time

The travel cost of each link is quantified with the volume and presence data collected from the loop detectors at each link by the network-monitoring module through time. In this research, the travel cost of link i during time interval k, T_{i,k}, is modeled as a function of the length of link i and its congestion level during k, i.e.,

\[ T_{i,k} = L_i (1 + C_{i,k}) \]

where, \( L_i \) = length of link i

\[ C_{i,k} = \sum \beta_j (P_{j,k} + V_{j,k})/(1 + V_{j,k}). \]

\( V_{j,k} \) = number of vehicles passed detector j in link i during k,
\( P_{j,k} = 1.0 \) if detector j is occupied by a vehicle at the end of k, 0.0 else.
\( \beta_j = \) weight for detector j in link i, \( \sum \beta_j = 1.0 \)

In the above formula, \( C_{i,k} \) represents the congestion level of link i during k on a 0 to 1.0 scale using only volume and presence detection commonly available from loop detectors. It has been successfully used as an index that quantifies level of congestion at each link for intersection signal control (9,10). Further, it is also possible to add certain physical characteristics of a route, such as number of turns, in the above travel cost function to reflect safety concerns of emergency-vehicle operators.
On-Line Route Selection

Once the current location of an emergency vehicle and its destination is determined, the route-selection module determines the best route that has the minimum travel cost for a given origin/destination pair under current traffic conditions. In the proposed strategy, a network is represented as a set of links/nodes and the well-known shortest-path algorithm developed by Dijkstra (8) is adopted to find the quickest route. The Dijkstra’s algorithm has been proven to result in the shortest-path from a single source on a weighted directed graph, where all edge weights have nonnegative values (11). In the proposed strategy, a given network is modeled as a set of directional links with nonnegative travel costs and the Dijkstra’s algorithm is applied to find the minimum travel cost route from the current location of an emergency vehicle to its given destination. Further, to ensure the safest traveling environment for an emergency vehicle during the preemption period, the proposed method also selects a specific phase combination for each intersection when multiple options exist in terms of available phases. Therefore, the output from the on-line route selection module includes both the minimum travel-cost route and the specific signal phase combination at each intersection during preemption as shown in Figure 2 for a hypothetical test network.

Dynamic Signal Preemption

Determining the right time to activate the signal preemption sequence for the intersections along the emergency route is of critical importance in reducing travel time of emergency vehicles and minimizing negative effects of signal preemption on normal traffic flow. Once the best route is determined for a given emergency situation, the dynamic preemption module sequentially activates the preemption procedure for the intersections on the route depending on the direction and location of an emergency vehicle. Figure 3 shows the current signal preemption sequence being implemented in Minneapolis, Minnesota, after a preemption request is received at an intersection. As indicated in the figure, the amount of time for the preemption procedure to be activated for an intersection $l$, $T_{act,l}$, varies depending on the specific state of a signal phase for a cross street when an emergency call is received, i.e.,

$$0 \leq T_{act,l} \leq P_{max,l}$$

where, $P_{max,l}$ is the maximum total time to complete the preemption sequence for intersection $l$ after an emergency call is received at the beginning point of the green phase for its cross street, i.e., Minimum Walk, Flash Do Not Walk, Yellow and All Red. In Minneapolis, $P_{max}$ generally equals to 20 seconds for most intersections. Therefore, the optimal amount of time needed to activate the preemption sequence at an intersection $l$ to provide the ‘best’ traveling environment for an emergency vehicle to clear the intersection can be considered as

$$P_{max,l} \pm w_{t,l}$$

where, $w_{t,l}$ can vary through time depending on several factors including the speed of an emergency vehicle, the status of the signal phase and traffic condition at intersection $l$ at time $t$.

Single/Variable Point Activation

Since it would be extremely difficult to calculate the optimum value of $w_{t,l}$ in real time for each intersection, in this research a simplified approach is developed to determine the activation point for each intersection by assuming a fixed value for $w_{t,l}$, which can be selected considering the average speed level of an emergency vehicle, $u_{EV}$, and the value of $P_{max}$ for a given network. I.e.,
the location of two potential activation points from the stop line of an intersection \( l \) can be formulated as follows:

\[
u_{EV} * (P_{\text{max},l} \pm w_l), \quad \text{where, } w_l \geq 0.
\]

In this study, two types of activation strategy were evaluated using microscopic simulation: single and variable point activation. Figure 4 shows the location of those two potential activation points on an emergency route. The single point method activates the preemption sequence when an emergency vehicle arrives at a pre-specified point, either A or B, while in case of the variable point activation, the activation is determined depending on the state of the signal phase at the intersection when an emergency vehicle arrives at the point A as follows:

when an emergency vehicle arrives at the first potential activation point A for the intersection \( l \),

if the signal phase of intersection \( l \) is Green for the travel direction of the emergency vehicle,
then Hold the current phase,
else if the signal phase is in the “Walk” stage for the cross street traffic,
then Start Preemption sequence,
else, Activate Preemption when the emergency vehicle passes the 2\textsuperscript{nd} activation point B.

The above procedure is sequentially applied to the intersections on the emergency route in the traveling direction of an emergency vehicle, and, depending on the distance between intersections, it is possible for more than two intersections on a given emergency route to be preempted at the same time. The variable point method tries to minimize the unnecessary preemption while providing green signals for an emergency vehicle with sufficient lead-time, so that the traffic at each intersection can be cleared enough for the safe and efficient passage of the emergency vehicle. In this research, both single and variable point activation methods were simulated and their performance was evaluated with different types of emergency routes.

**Signal Recovery Procedure**

As soon as an emergency vehicle clears an intersection, the signal recovery procedure kicks in to restore the original cycle and/or coordinated timing settings of the intersection. The current signal operational policy in Minneapolis, Minnesota, allows only the “Walk” interval in each signal phase to be adjustable during the transition period, while other intervals such as “Flash Do Not Walk” and “Yellow/All Red” must be fixed for safety reasons. Therefore, the signal recovery procedure developed in this study restores the original timing settings by adjusting the amount of “Walk” interval of the cross street, i.e., blocked roadway during preemption.

Figure 5 illustrates the adjustment process for the “Walk” time of cross street to recover the original signal settings of a pre-timed intersection. When preemption is activated for an intersection, the proposed method keeps tracking the original timing plan of the intersection in the background mode on a global time scale. As the preemption terminates, the signal phase starts to change to provide Green time for the cross street, i.e., the blocked roadway during preemption, by changing the Green light of the main street to Yellow and then All Red. Depending on the location where the All Red interval of the main street ends on the original timing plan being tracked in the background mode, the proposed procedure either extends or shortens the Walk time of the cross street, so that the resulting timing settings can catch up to the original timing plan at the end of the current signal phase for the cross street. For example, in the case 2 shown in Figure 5, the All Red interval of the main street ends at the Flash Do Not Walk interval of the main street on the original timing plan. In this situation, the Walk interval of the cross street is extended
to the originally scheduled Walk time for the next phase, so that the regular timing schedule can be restored at the end of the next phase. While the procedure shown in Figure 5 indicates a direct recovery approach within one cycle for a pre-timed control intersection, the proposed method can be extended to a multiple-cycle transition period for incremental adjustment of timing settings.

EVALUATION OF PROPOSED ROUTE-BASED DYNAMIC PREEMPTION STRATEGY

The proposed route-based dynamic preemption strategy is evaluated with a microscopic simulation software, Vissim (12), whose main simulation function can interact with an external module that can set the state of each signal light in a given network every 1/10th second. One key feature of the simulation software used in this research is its capability to install a set of detectors that can only detect pre-designated emergency vehicles that are generated at pre-specified times during simulation. However, the current version only allows the simulation of emergency vehicles following pre-specified routes, i.e., an emergency route can not be either generated or changed during simulation. Therefore, the evaluation conducted in this research focused on the effectiveness of the proposed dynamic preemption strategy over the existing intersection-by-intersection preemption method for a given set of pre-determined routes.

Sample Network and Calibration of Simulation Model

In this study, the University of Minnesota Campus in Minneapolis, Minnesota, is used as the sample network, where the proposed preemption method was implemented and evaluated using microscopic simulation. Figure 6 shows the sample network with 33 signalized intersections that are currently operated in a pre-timed, offset-based coordinated mode. The geometric data for the campus network was collected from the aerial photos purchased from the Metro Council, Minnesota, while the detailed traffic data for the intersections in the network, including traffic volume, signal timing plans, preemption sequence and the parameters for existing preemption systems, were provided by the Traffic Operations Center (TOC), City of Minneapolis. Further, to calibrate the simulation model, the travel time data of emergency vehicles in the sample network with existing preemption systems were also collected during two afternoon periods on two weekdays in cooperation with the University of Minnesota Police Department. Figure 6 also includes the three routes, i.e., Route 1-3, where the emergency vehicle travel time data were collected for this study. Most of the signalized intersections on Route 1 and 2 have the optical preemption systems, while none of Route 3 has any preemption device. For each route, a total of four test-runs were made with a police car equipped with the light-beam emitter. In this research, the existing intersection-by-intersection preemption strategy was also modeled and coded into an external controller module. To simulate existing light-beam or sound-based preemption systems with different detection ranges, each link in the sample network is equipped with the loop detectors installed every 15 meters. Therefore, depending on the detection range of a given detection system, a particular detector set can be programmed to detect only emergency vehicles. The distance between the detector set for emergency vehicles and an intersection can be adjusted to reflect the detection range of a given preemption system.

Using the travel time data of emergency vehicles collected in the sample network, the simulation software was first calibrated to make the simulation model reflect the real traffic environment as much as possible. For this calibration, the existing intersection-by-intersection preemption strategy being implemented in the sample network was simulated for the three routes...
where the emergency vehicle travel time data were collected. The resulting simulated travel time data of the emergency vehicles were compared with the real data and the difference was minimized by adjusting the speed range of an emergency vehicle during simulation and the detection distance of the existing preemption system in the sample network. Specifically, the speed profile of an emergency vehicle was set to 60 – 130 km/hr, while the detection range was determined as 200 – 300 meters. Table 1 shows the simulated and actual travel time data of an emergency vehicle for the three routes in the sample network. To reflect the effects of stochastic simulation, five random seeds were used for each case and their results were averaged.

**Performance Evaluation of Route-based Dynamic Signal Preemption Method**

Finally the proposed route-based dynamic preemption method is evaluated in the sample network using Vissim. As mentioned before, the current version of the simulation software used in this study can not generate an emergency route during a simulation period, i.e., a route for a particular vehicle must be pre-specified before simulation starts. Because of this limitation, the on-line route-selection module developed in this study could not be linked to the simulation software in this work. Therefore, the evaluation performed in this paper focused on the effectiveness of the proposed, sequential dynamic-preemption strategy over the existing intersection-by-intersection preemption method for a set of the pre-specified routes in the sample network. Figure 6 also shows four different types of routes, i.e., Route 1-4, where the proposed strategy was simulated and its performance was compared with that of the existing intersection-by-intersection preemption method. Among the routes tried in this study, Route 1 and 3 are relatively simple straight routes with few turns, while Route 2 is the longest route with the most number of traffic signals. Route 4 has the most number of left-turns in a relatively short distance.

For evaluating the dynamic preemption with single-point activation, three different activation points upstream of each intersection, i.e., 330m, 400m and 470m from the intersection stop line, were simulated with different random seeds. Those three points were located within 15-20 second range of an emergency vehicle traveling at 80 km/hr. It can be noted that the maximum amount of time needed for preemption at the intersections in the sample network is 20 seconds. The variable point preemption method used two potential activation points, i.e., 15 and 25 second driving distance at 80 km/hr from each intersection, i.e., 330m and 560m from the stop line. Each case was simulated for a 45-minute period with the same peak-hour demand for the sample network, where the emergency vehicle was generated at 15th minute into the simulation. Once generated, the emergency vehicle traveled the pre-determined route and the signals on the route were dynamically preempted following pre-specified preemption strategy for each case. For a fair comparison, a common set of 6 different random seeds was used for the simulation of each preemption strategy and their results were averaged. Table 2 includes the simulation results from each preemption strategy in terms of the network-wide traffic performance including total vehicle-hours and average delay per vehicle after preemption started until the end of simulation period. Figure 7 shows the simulated travel time of an emergency vehicle on each route with different types of preemption strategies evaluated in this study.

As indicated in Figure 7 the simulation results clearly show the advantage of the proposed route-based dynamic preemption strategy over the existing method in terms of the emergency vehicle travel time. As indicated in Figure 7, all four routes evaluated in this study exhibit consistently reduced travel times of an emergency vehicle with the dynamic preemption strategies compared with those of the intersection-by-intersection preemption. Further, the relatively long and complicated routes, Route 2 and 4, showed significantly larger reduction of the emergency vehicle travel time.
travel time than the simpler routes, i.e., Route 1 and 3, over the existing intersection-by-intersection
clearance method. The Route 2, the longest with the most number of signals, shows 9-11% improvement, while the results with the Route 4, the most complicated route, indicate 10-16\%
reduction of travel time over the existing method. While the results with Route 1 and 3, which are relatively short and straight routes, do not show significant reduction of the emergency vehicle
travel time, i.e., 3-11\% reduction, they still exhibit consistently lower travel time patterns with the
proposed dynamic preemption methods. It can be also noted that, in case of Route 2, the location
of preemption activation points did not make significant differences in terms of the travel time for
an emergency vehicle among different dynamic preemption methods. This can be partially due to
the current limitation of the simulation software in modeling the behavior of the vehicles reacting to
an emergency situation, i.e., an emergency vehicle needs to maneuver among normal vehicles to
pass normal vehicles. It can be observed that, with the single-point activation method, while no clear pattern can be found between the location of the activation point and the emergency vehicle travel time, the cases with the furthest activation point, i.e., 470m, consistently produced the most efficient signal preemption in terms of the emergency vehicle travel time. It is also interesting to
note that the variable-point activation strategy does not show significant advantage over the single-
point activation method in terms of reducing the emergency vehicle travel time.

Table 2 shows the network-wide traffic performance after an emergency vehicle entered the
network until the end of the simulation period. As shown in this table, the total vehicle-hours and
average delay per vehicle show an interesting pattern, i.e., the results with Route 1 and 3, the
simpler and shorter routes than Routes 2 and 4, indicate slightly, but consistently improved
network-wide performance with the dynamic preemption, while the cases with the longer and more
complicated routes, Route 2 and 4, exhibit a clear pattern of the degraded performance in terms of
average delay. However, the magnitude of the degradation is relatively small ranging from 5-9\%
compared with the reduced travel time of emergency vehicles. This indicates the efficiency of the
proposed strategy by reducing unnecessary preemption in a given network, thus minimizing the
delay because of preemption.

CONCLUSIONS
This paper presented a route-based dynamic preemption method for emergency vehicles and
its evaluation results in an example network using a microscopic simulation model. The proposed
strategy sequentially preempts the traffic signals at the intersections along the optimal route with
advance activation, so that the traffic queue at each intersection can be cleared for the approaching
emergency vehicle. Due to the limitations of the simulation software, the on-line route-selection
method developed in this study could not be tested in the current phase. The evaluation results with
pre-specified emergency routes show substantial reduction of the emergency vehicle travel time for
relatively long and/or complicated routes compared with the existing intersection-by-intersection
preemption method, while the magnitude of the benefit can vary significantly depending on the
length and types of a route. Further, the network-wide performance measures with the proposed
dynamic preemption method were very compatible with those from the existing intersection-by-
intersection clearance method. The performance comparison between single and variable-point
activation indicates no significant advantage with the more complicated variable point method,
which implies the practical applicability of the proposed simple activation strategy. Future research
includes the development of an efficient clearance method for the user-specified route with a
decentralized approach, the enhancement of the simulation model to realistically reflect the behavior
of vehicles responding to an emergency vehicle. Research on determining the optimal location of the activation point in real time for more efficient preemption also needs to be continued.

Acknowledgement
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Figure 1  Simplified structure of proposed strategy
Figure 2  Test results of On-line Route Selection Module with an example hypothetical network
Case 1: Complete ‘Minimum Walk’ interval and go to ‘Flash Do Not Walk’, continue to Yellow and ‘All Red’ before switching to Green phase for Main Street, i.e., an emergency route for a given situation.

Case 2: Go to ‘Flash Do Not Walk’ immediately. Complete Yellow and ‘All Red’ before switching to Green for Main Street.

Case 3: Complete the current signal sequence for cross traffic before switching.

Figure 3  Current Signal Preemption Sequence in Minneapolis, Minnesota
Figure 4  Example Activation Points for Dynamic Preemption
Original Signal Timing Schedule

- $W_m$: Main Street Walk Interval
- $W_c$: Cross Street Walk Interval
- $F$: Flash Do Not Walk
- $Y_m$: Main Street Yellow
- $Y_c$: Cross Street Yellow
- $AR$: All Red

Figure 5  Signal Recovery Process
Figure 6  Sample Network and Example Emergency Routes
Figure 7  Simulated Travel Time of Emergency Vehicle for Different Routes
Table 1. Measured and Simulated Emergency Vehicle Travel Time (min:sec)

<table>
<thead>
<tr>
<th>Route</th>
<th>1st</th>
<th>2nd</th>
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<th>4th</th>
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Table 2. Simulation Results from Different Signal Preemption Strategies

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<td>Route 2</td>
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<td>Average Delay (sec)</td>
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<td>Route 3</td>
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<td>Average Delay (sec)</td>
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<td>Average Delay (sec)</td>
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* SPA: Single Point Activation, e.g., 330 m from the intersection stop line.
** Activate either 330 m or 560 m from the stop line depending on signal status.