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Dynamic Preemption Algorithm to Assign Priority for Emergency Vehicle in Crossing Signalised Intersection

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Abstract. Emergency vehicle (EV) services save lives around the world. The necessary fast response of EVs requires minimising travel time. Preempting traffic signals can enable EVs to reach the desired location quickly. Most of the current research tries to decrease EV delays but neglects the resulting negative impacts of the preemption on other vehicles in the side roads. This paper proposes a dynamic preemption algorithm to control the traffic signal by adjusting some cycles to balance between the two critical goals: minimal delay for EVs with no stop, and a small additional delay to the vehicles on the side roads. This method is applicable to preempt traffic lights for EVs through an Intelligent Transportation System. A Matlab-Vissim Interface was implemented to simulate the intersection and apply the proposed algorithm. The results show a significant decrease in delays for both EVs and other traffic.

1. Introduction

The Emergency vehicle preemption (EVP) is an advantageous solution for EVs at intersections, to reduce their travel time by providing right of way [1]. Different types of EV detection techniques are applied, including the use of light, sound, pavement loops, radio broadcast, and push buttons to detect the arrival of an EV at an intersection [2].

In these systems, preemption of each intersection occurs only once the EV has arrived, which means that the EV has to stop at each intersection as it waits for the queue at the intersection to be flushed. Besides, the current EVP process might be more complicated, such as during peak hour traffic or after-event traffic. During these high traffic times, the way of an EV is heavily jammed because of the increased delays at local intersections due to a lack of clearance at downstream [3].

Emergency vehicle preemption has several advantages. It can quicken the response of emergency operation, offer safety for EV and other vehicles, and save the public cost because of protecting property from damage [4]. Despite the application of EVP to decrease the travel time of emergency vehicles, it can affect overall traffic negatively [5].

Much research has tried to preempt traffic signals for EV. They applied different techniques to detect the EV when it approaches the intersection. However, most of these techniques used relatively short or limited detection regions. This means that these techniques do not consider the queue length. The queue length could be short, medium, or long. Thus, because the pre-emption, operation will start only when the EV approaches the intersection; it will be part of the queue length and be engaged in the congestion. This can result in a significant delay and increasing emergency vehicle travel time. Furthermore, research was performed at six locations in New York City to investigate the advantages
and disadvantages of EVP [6]. They found that although the application of EVP systems modified the
ev response, it also disrupted the coordination of the traffic light systems [6].

Queensland, Australia developed and applied an emergency vehicle priority system (EVPS). This
system is part of an Intelligent Transport System (ITS). The EVPS was examined by ten ambulances
and ten fire engines in 50 intersections communicated with EVPS. All the Gold Coast ambulance and
fire vehicles were supported with EVPS along with 40% of total intersections across Queensland. In
Brisbane, a few north-western suburbs were tested as a trial implementation of EVPS [7]. However,
this system assumed a fixed queue clearance time in its controller calculations. This constant value
does not depend on the average queue length, which might result in a significant delay for EV at
highly congested intersections and additional delays for other vehicles at uncongested intersections.

There is no research that determines the exact position of the emergency vehicle in which the
preemption process must start to balance between minimum travel time and delay for an emergency
vehicle and minimum additional delay for other vehicles.

This paper developed a Dynamic Preemption Algorithm (DPA) that can minimise the travelling
time, delay, and the number of stops for emergency vehicles, and protect the traffic from detriment by
ensuring minimum additional delay for other vehicles. This algorithm is also responsible for
determining the exact second during the phasing cycle of the traffic signal at which the preemption
must be started, depending on the Global Positioning System (GPS) information received from to the
EV.

2. Related Work
Assigning priority to EVs was popular long before the implementation of ITS preemption
technologies. There are some factors that led to the application of ITS strategies to grant a particular
green interval to EVs while assuring red lights to conflicting approaches [8]. Some of these factors are
safety concerns, increasing of traffic congestion, besides the modification of transportation
technologies. The start of preemption history was in 1929 when the American Engineering Council
publication reported the necessity for supplemental methods for EV operation in a coordinated scheme
[9]. The development of combining preemption in signal systems technology was in 1960s [8]. This led
to the implementation of the first kind of preemption system in the early 1970s [10].

In 1979, 3M implemented a new system, which could prioritise preemption requests [9]. This was
recorded as the start of Transit Signal Priority with the system providing two priorities levels, the
higher one for emergency vehicles and the lower one for transit vehicles.

The brand name Opticom was assigned to these preemption systems, which constituted a stand-
alone emitter part required for EVs and transit vehicles. Then, the strobes were replaced with infrared
emitters and detectors, because of the public use of strobe lights to mislead traffic signals [11]. After
that, in 1992, 3M supplemented encryption codes to its infrared transmitters, to prevent wrong
preemption requests being created by hackers [9]. Currently, technological improvements, such as the
use of Global Positioning System (GPS) to determine the latitude, longitude, speed, and direction of
emergency vehicles, came into everyday use [9]. Emergency vehicle preemption has experienced
significant developments with advancements in ITS. The hardware of EVP systems has been modified
to use automatic vehicle location using GPS [9] and Vehicle to Road Side Communication, which uses
encrypted radio and infrared waves. Although, the preemption hardware has been modified, the
preemption logic is still the same as before. Most of the current preemption systems include three
stages: detection, preemption, and transition, which require detecting EV to trigger the traffic light
controller to start the preemption process.

The most common technologies, which are applied in the current preemption systems, are sound-
based systems, radio-based systems, light, and infrared systems [4, 10]. The issues in the light and
infrared preemption systems are they need a clear line of sight, and the weather can easily influence
them REF.

Although sound alert systems do not depend on line of sight, the limited range restricts them,
because the sound loudness is limited to a specific level to prevent conflict with the nearby traffic
lights REF.
The disadvantage of radio-based systems is their limited range, so the preemption will start when the EV is part of the queue at intersections. In addition, the radio systems preempt all traffic lights in proximity rather than just those along the EV’s route. Thus, most of the current EVP systems include an issue of limit proximity of EV detection area. Thus, the EV must be close to the intersection to trigger the preemption process. This strategy will not ensure minimum travel time and delay for an EV, because it might be engaged in the queue before the traffic signal preemption starts.

According to the current research, EV travel time can be effectively minimised by applying the route wide preemption methods [12]. Utilising communications technologies between EVs and traffic light controllers can support the EVP systems in a real-time environment. These technologies can help in modifying the EV’s response with increasing congestion. Currently, these advanced technologies, such as the use of GPS, are applied in preemption systems to estimate the position, speed, and direction of EVs [9].

Therefore, some EVP systems tried to use GPS to address the proximity issue. However, they do not take into consideration the possibility of queue length variations, which can affect negatively the travel time of EV and other vehicles.

Some studies in New York City examined and estimated the influence and advantages of EVP [12]. These studies proved enhanced EV operation at all six locations, but also recorded confusion in the coordination of the signal systems. The required recovery was more than four-cycle lengths. Besides, results indicated an average rise in traffic delay of 4–58 % [12].

From the above discussions, we conclude that most of the current preemption systems do not consider the queue length at intersections during the preemption operation, which does not satisfy minimum delay for EVs. However, the other part of preemption systems that applies is that wide-range detection does not consider minimising the negative impact on other vehicles.

Hence, a balance is required between these two important needs, by determining the best time through the cycles in which the traffic signal preemption must start to achieve these two goals.

3. Dynamic Preemption Algorithm
This research aims to develop a dynamic preemption algorithm that can preempt traffic signals for EVs with unlimited GPS-based detection range. This algorithm must determine the specific location of an EV at which point the preemption of the traffic signal must start. The choice of this location, which corresponds to a particular second within the phasing cycle of the intersection, must balance between two critical needs: minimum travel time to EV equal approximately to its theoretical travel time and minimum or slight additional delay for other vehicles at the same intersection.

3.1. Network Model Assumption
It is assumed that the EV navigates through roads supported by Intelligent Transportation System where the EV is provided with GPS to communicate with satellite, which communicates in its turn with all traffic-light controllers along the EV route. In addition, we assumed that traffic signals also can compute approximately the average queue lengths in any approach within each intersection located along the EV route and have an accurate estimation of traffic arrival rates.

3.2. The Proposed Dynamic Preemption Algorithm
The primary goal of the proposed algorithm is to minimise the EV delay, as much as possible, to make the travel time of EV approximately equal to its theoretical travel time without stopping. The second goal is to reduce the additional delay to the other vehicles in the side road and keep the network performance stable after the EV has crossed the intersection. The proposed algorithm is based on the idea of adjusting the cycles of the traffic signals at all intersections located along the route. The adjustment occurs in one or more cycles to ensure enough green light for an EV to pass the intersection with minimum delay and no stops by borrowing some green-light time from other approaches. Besides, the adjustment also includes returning some seconds to these approaches after the EV has passed the intersection. Thus, we named the suggested strategy as borrow and return. The role of the dynamic preemption algorithm is to decide when and how many seconds must be borrowed.
or returned to achieve the research goal. The proposed algorithm can be summarised in the following steps:

- Calculating theoretically the expected arrival time \( t_a \) of EV to the intersection from equation (1):
  \[
  t_a = \frac{D}{V}
  \]  
  (1)

  Where:
  \( D \) = the distance between the start point and the intersection
  \( V \) = EV operating speed

- According to the research assumptions, each intersection controller will be triggered to calculate the queue flushing time from equation (2):
  \[
  \text{The average queue flushing time} = V_t \times N
  \]  
  (2)

  Where:
  \( V_t \) = The required time for each vehicle to pass the intersection through the green phase
  \( N \) = Average number of vehicles in the queue (includes both moving and stationary queue) during the red phase

- To ensure clearing the way for EV without the need to decelerate or accelerate its speed when it is so close to the queue vehicles, an additional factor \( d_a \) will be added to the queue flushing time as shown in equation (3). Its value was selected to be two seconds.
  \[
  \text{Safe queue flushing green time} (g_f) = \text{average queue flushing time} + d_a
  \]  
  (3)

- Determining in which cycle, phase, and interstage the EV expected to reach the intersection. This cycle is called the arrival cycle (AC) and the specific time (second) at which the EV arrives is called the expected arrival time \( t_a \) as mentioned previously.

- There is another important time to be calculated in the cycles in which the flushing the queue must be started to clear the way for EV. This time (second) is called Queue length indicator and symbolised by \( s \), where \( s \) is calculated from equation (4):
  \[
  s = t_a - g_f
  \]  
  (4)

In Figure 1, the expected arrival time of the EV is shown at \( t_a \), in phase3. Equation 4 then dictates that to avoid impeding the EV, queue flushing must start at \( s \), in phase2. Thus, to help EV pass the intersection with no delay and no stop, the interval of time within the AC, that is specified from \( s \) to \( t_a \), must represent the green light for the EV approach as clarified in Figure 2.

**Figure 1.** The Phase Sequence before Preemption  
**Figure 2.** The Phase Sequence after Preemption

The value of \( t_a \) and \( s \) will change depending on the EV start time and the average queue length. This means that the expected cycle, phase, and interstage for the EV to arrive at the intersection will be different too. Thus, to be able to switch the green light for EV within the priority interval (between \( s \) and \( t_a \)), we suggest the following steps, to balance between the main goals of this paper: minimum travel time for EV and slight increase in additional delay to the other vehicles in the same intersection:

A) Borrow Stage

- Shifting phases: this means shifting phase/s with a specific time interval to give enough green to the EV approach phase.
• Skipping phases (symbolised as creditor phase/s): which means cancelling phase/s from the phasing sequence
• Shortening one or more phases (symbolised as creditor phase/s): this means decreasing the green time of specific phase with considering the minimum green condition
• Extend the green light for EV approach (symbolised as debtor phase): This means increasing the green time of specific phase with considering the maximum green extension condition

B) Return Stage
• Shifting phases: this means shifting phase/s with a specific time interval.
• Skipping phases (normally the EV approach phase, which is symbolised as debtor phase/s): This means cancelling phase/s from the phasing sequence
• Shortening one or more phases (debtor phase): this means decreasing the green time of specific phase with considering the minimum green condition
• Extend the green light for the creditor phase/s: this means increasing the green time of specific phase with considering the maximum green extension condition

Results depend on which phase will be debtor, which phase will be creditor, and what exactly should be the values of $t_a$ and $s$. Thus, the proposed DPA determines when the preemption must be started and how many seconds must be borrowed/returned and from/to which phases respectively. To simplify that, we investigated and classified 15 different cases with more than 45 individual cases. For each specific case, we suggest a specific strategy includes some of the previous steps to access our research goal.

4. Experimental Results

To examine the performance of the proposed algorithm, we simulate one intersection using a Vissim microscopic simulator. We have created a Matlab-Vissim interface to program the DPA steps and to be able to apply it to the simulated intersection. The duration of the simulation run is approximately 10 minutes with 5 minutes as warm up period. The simulated scenarios are No Preemption (NP), Fixed Preemption (FP which means fixed queue flushing time), and the proposed Dynamic Preemption algorithm (DPA) to preempt EV. For each scenario, we applied different levels of congestion (low, medium, and high) by changing the volume of vehicles supplied to the intersection to investigate the performance of the proposed algorithm during different congestion conditions.

The measurements that were used for comparison of these three scenarios included average travel time, average delay for the emergency vehicle navigation, number of stops, average speed of EV, maximum additional delay to other vehicles, and average additional system delay as compared with the no priority scenario. For each scenario, the simulation was run for approximately 90 runs with random seed numbers (30 runs for each level of congestion), and the median of the measures was calculated to ensure covering all the distributed results. Table (1, 2, 3, and 4) show the performance measurements of EV for the three scenarios (NP, FP, and DPA) in the three levels of congestions (low, medium, and high). Table (5 and 6) show the impact of EV preemption (FP and proposed DPA) on the other vehicles in the all approaches of intersection including side-road traffic. The impact represented by two calculations, the maximum additional delay resulted in any approach and average additional delay of all vehicles in the intersection.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Level of Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Congestion</td>
</tr>
<tr>
<td>NP</td>
<td>28.715</td>
</tr>
<tr>
<td>FP</td>
<td>0.425</td>
</tr>
<tr>
<td>DPA</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1. EV Delay
Table 2. EV Travel Time

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low Congestion</th>
<th>Medium Congestion</th>
<th>High Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>106.4</td>
<td>129.59</td>
<td>163.85</td>
</tr>
<tr>
<td>FP</td>
<td>78.3</td>
<td>79.97</td>
<td>89.975</td>
</tr>
<tr>
<td>DPA</td>
<td>77.79</td>
<td>78.85</td>
<td>78.15</td>
</tr>
</tbody>
</table>

Table 3. EV Average Speed

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low Congestion</th>
<th>Medium Congestion</th>
<th>High Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>43.825</td>
<td>37.87</td>
<td>30.336</td>
</tr>
<tr>
<td>FP</td>
<td>59.556</td>
<td>57.495</td>
<td>52.345</td>
</tr>
<tr>
<td>DPA</td>
<td>59.925</td>
<td>59.485</td>
<td>59.8</td>
</tr>
</tbody>
</table>

Table 4. Number of Stops

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low Congestion</th>
<th>Medium Congestion</th>
<th>High Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>FP</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DPA</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5. Additional Average Delay to other Vehicles

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low Congestion</th>
<th>Medium Congestion</th>
<th>High Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP</td>
<td>0.11</td>
<td>1.178</td>
<td>2.15</td>
</tr>
<tr>
<td>DPA</td>
<td>0.19</td>
<td>1.575</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Table 6. Maximum Additional Delay to other Vehicles

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low Congestion</th>
<th>Medium Congestion</th>
<th>High Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP</td>
<td>6.71</td>
<td>13.08</td>
<td>23.285</td>
</tr>
<tr>
<td>DPA</td>
<td>4.53</td>
<td>11.825</td>
<td>21.7</td>
</tr>
</tbody>
</table>

The results show that our proposed algorithm decreases the travel time 52.3% as compared with a NP scenario, while the reduction is only 45% when applying the FP scenario. The results also show that the proposed DPA helps the EV to navigate and cross the intersection with no delay (zero delays and no stops) in all the different congested scenarios (low, medium, and high), while in the FP method the EV
still have non-zero delay (11.845 sec as an average in the high congested scenario) and non-zero stops, in particular in the high congestion situation. It is also shown that the EV speed was equal approximately to the theoretical speed (60 m/sec) when applying the proposed DPA, while it still less than this value when applying the FP method, especially in the high congested scenario. Although the proposed DPA results in a slight increase in average delay (3sec) for the other vehicles as compared with the FP time preemption method, the maximum additional delay is less than the maximum result from applying the FP case in the three levels of congestion. Figure 3 shows a comparison of median travel times in different levels of traffic (low, medium, and high) for the EVs to cross the intersection. As shown, the average travel time of EVs was decreased from the NP case to the FP case, and it was further reduced in the case of the proposed DPA. Figure 4 shows a comparison of the median delay time for the three scenarios at different levels of congestion (low, medium, and high) for an EV to cross the intersection. As shown, the median delay time of EV decreased from the NP case to the FP method, and it was zero in the case of the proposed DPA. Figure 5 shows a comparison of the median speed of EV for the three scenarios at different levels of congestion (low, medium, and high) to cross the intersection. As shown, the median speed of EV decreased from the NP case to the FP method, and it was further reduced in the case of the proposed DPA.

5. Conclusion
The proposed DMA to preempt traffic signals for EV was evaluated using a Matlab-Vissim communication interface simulation. The results proved that DMA is efficient in helping EVs to cross an intersection with zero delay, no stops, and with travel time equal approximately to its theoretical minimum travel time. It also proved that the DMA enables the EV to navigate and cross the intersection with approximately its maximum operating speed. The results also show that the proposed algorithm has less impact on other vehicles in the intersection than the fixed preemption method. Overall, the evaluation proved the dynamic preemption method works better than the fixed preemption method, which is currently applied as an EV preemption method at many intersection traffic lights. This indicates the reliability and efficiency of the proposed methodology to improve the emergency response in different levels of congestion. This paper represents the first step in our research, and the work is proceeding to apply the proposed algorithm in a multi-intersection network to investigate its impact on the surrounding intersections and on other vehicles in the network.

Reference


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