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Investigating the proactive avoidance of pre-emption conflicts with emergency vehicle signal pre-emption and route selection integration

C. R. D. Broeksma* and J. F. Bekker*

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Abstract

The study aims to improve average emergency vehicle (EV) response times by proactively avoiding pre-emption conflicts by integrating emergency vehicle signal pre-emption (EVSP) and route selection. Pre-emption in this work means to anticipate an emergency vehicle approaching a signalled intersection, and attempting to ensure it is provided with right of way. While literature highlights the success of EVSP strategies, particularly when integrated with route selection, few strategies consider pre-emption conflicts that can cause delays to EVs. An EVSP and route selection strategy capable of proactively avoiding pre-emption conflicts was subsequently proposed in this study. Using simulation modelling, the two strategies were compared in a series of carefully constructed experimental runs. To test the robustness of the proposed strategy, each experimental run was configured according to a unique combination of variables. It was empirically observed that, while not robust against these variables, the proposed strategy could perform equally well or better than the reference strategy (when considering average EV response times) in most instances. This indicates that an EVSP and route selection strategy capable of proactively anticipating and attempting to avoid pre-emption conflicts is a promising approach to reducing the response times of EVs.

Key words: Emergency vehicle, Emergency vehicle signal pre-emption, Pre-emption strategies, Pre-emption conflicts, Response time reduction, Route selection, Simulation modeling.

*Department of Industrial Engineering, University of Stellenbosch, Private bag X1, Matieland, 7602, Republic of South Africa, email: jb2@sun.ac.za

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1 Introduction

An increasing number of individuals are moving to urban areas around the world, with more than 6.3 billion people expected to live in urban areas by 2050 ([1]; [2]). While urbanisation has numerous benefits, it comes with drawbacks [1]. According to the Organization for Economic Cooperation and Development (OECD) and European Commission [3], Lawrence [4], Kodire *et al.* [5], and Shelke *et al.* [6], one particular drawback is the fact that urbanisation typically causes overwhelming of road infrastructure, due to large numbers of vehicles present in cities. This, in turn, leads to traffic congestion and delays on urban roads. These congested roads could hinder the ability of emergency vehicles (EVs), such as ambulances, police cars, and fire trucks, to reach their destinations as quickly as possible. Bieker-Walz & Behrisch [7], Mu *et al.* [8] and Su *et al.* [9] state that the presence of traffic congestion makes it challenging for EVs to arrive at their destinations in a fast and safe manner. Oza & Chantem [10] agree with this statement, mentioning that it negatively impacts the "*timely deployment of emergency response systems*".

EVs must have minimal response times, as this enhances the possibility of saving lives ([11]; [6]) and property ([12]; [13]; [14]). While EVs typically use sirens and light bars to notify non-emergency vehicles (non-EVs) that they are approaching and on their way to an emergency [14], this does not guarantee that the path of an EV remains unobstructed. Qin & Khan [15] mention that non-EVs sometimes cannot move out of the way to allow an approaching EV to pass. This can occur at signalled intersections in some urban areas, where street-side parking limits the space available to non-EVs when attempting to let an EV pass. According to Shelke *et al.* [6] and Wang *et al.* [16], long stagnant vehicular queues are common on urban roads. When waiting at a red traffic light, these stagnant queues can block approaching EVs ([7]; [6]), preventing them from traversing the signalled intersection in the shortest time possible. In cases where an EV can pass a queue of non-EVs ahead of a signalled intersection, the EV still faces the risk of being involved in an accident when running the red light. According to Bieker-Walz & Behrisch [7], EVs are eight times more likely to be involved in accidents than non-EVs. Both [7] and Petrică *et al.* [17] state that the majority of EV-related accidents occur when EVs run red lights, even though their light bars and sirens are activated.

EVSP strategies are used to address EV delays at signalled intersections ([19]; [20]; [8]) – being some of the most successful approaches in doing so [17]. EVSP strategies provide EVs with right-of-way at signalled intersections by switching the signal green in their favour [18]. Doing so ensures that an EV has a green wave en route to the scene of an emergency [20], which ensures safe and rapid intersection traversal. Route selection is another approach used to reduce EV delays and shorten response times, which involves routing an EV along the fastest route to its destination. Shaaban *et al.* recommend using route selection in conjunction with EVSP. Both Su *et al.* [9] and Kamble & Kounte [14] agree, mentioning that a variety of studies propose strategies aimed at reducing EV response times by using both traffic signal pre-emption and route selection. Integrating EVSP and route selection is effective, as route selection ensures that EVs follow the quickest route to the scene of an emergency, while EVSP ensures that an EV can traverse signalled intersections rapidly and safely along the way ([13]; [21]; [15]).

The paper is structured as follows: Some related work is discussed next to show the research gap, followed by a description of the methodology applied to develop strategies for proactive pre-emption of traffic intersections. The strategies were modelled and compared with 152 experimental scenarios. Finally, conclusions are presented, as well as suggestions for future work.

2 Related work

Emergency vehicle signal pre-emption (EVSP) has been well-researched since being proposed in 1929 [8]. This section reviews existing EVSP strategies to show the research gap.

Humagain *et al.* [13] conducted a systematic review of route optimisation and pre-emption methods for EVs, in which they analysed 72 research articles related to EVSP by multiple authors. These articles proposed various strategies for enabling EVSP and route selection. Humagain *et al.* [13] identified some aspects of EVSP that have not received sufficient research. One of these aspects is that existing EVSP strategies are typically unable to consider/address cases in which two or more EVs are required to traverse the same signalled intersection from conflicting directions, causing pre-emption conflicts. As the systematic review of Humagain *et al.* [13] did not consider EVSP-related research articles published after 2018, newer articles were also reviewed to establish whether this perceived research gap still exists. In doing so, a literature survey by Kamble & Kounte [14] was studied. After surveying a variety of existing EVSP strategies, they found that most existing ones are not designed to serve multiple EVs simultaneously. They subsequently stated that it is vital to extend existing pre-emption strategies to make them capable of doing so.

A literature review was conducted to identify existing EVSP strategies that consider cases where multiple EVs require conflicting pre-emption at a given signalled intersection. It was found that both Bieker-Walz & Behrisch [7] and Cao *et al.* [22] propose EVSP strategies that can address conflicting pre-emption phases among EVs. The strategy proposed by Bieker-Walz & Behrisch [7] does this by establishing the order in which pre-emption is awarded to each affected EV. In contrast, the strategy by Cao *et al.* [22] aims to minimise EV delays by optimising the timing of the respective signal phases. These strategies are thus able to *manage* pre-emption conflicts *reactively*, potentially reducing delays caused to EVs by these conflicts. While reactively managing pre-emption conflicts can reduce delays to affected EVs, they will continue to be hindered by the conflicts (as they will still exist); it might just be less severe.

After considering the literature surveys conducted by Humagain *et al.* [13] and Kamble & Kounte [14], as well as analysing the works by Bieker-Walz & Behrisch [7] and Cao *et al.* [22], it was found that the majority of existing EVSP strategies do not consider the eventuality of pre-emption conflicts. While some do consider these conflicts, they do so *reactively*, and it is deduced that there does not appear to be an EVSP strategy that attempts to *avoid* the occurrence of pre-emption conflicts in a *proactive* manner. The study presented in this paper investigated whether pre-emption conflicts can be avoided *proactively* by integrating EVSP and route selection.

3 Methodology

Two EVSP and route selection strategies were developed – one having the novel functionality of attempting to avoid pre-emption conflicts proactively – and the other being a reference strategy without the novel functionality. These two strategies were then compared in a series of simulation-based experiments to determine if the proposed strategy results in shorter EV response times. The proposed and reference strategies are described in the following subsection, with the simulation models used during the experimentation being described after that.

Some assumptions were needed for the strategies: It was assumed that technology that reports the state of the traffic network is available. This includes the phases of traffic signals at the various intersections and the lengths of vehicular queues waiting at the stop lines of red traffic signals. It was assumed that each intersection in a road network is a signalled intersection capable of executing pre-emption. The worst case was assumed regarding EVs passing non-EVs, i.e., non-EVs not making way for approaching EVs. It was further assumed that the traffic network is in a steady state. Lastly, the study assumed left-hand drive and that EVs have an operating speed of 70 km/h.

3.1 Descriptions of developed strategies

The first strategy (referred to as the *proposed strategy*) is described, followed by the reference strategy.

3.1.1 Proposed strategy

In its simplest form, the proposed strategy can (1) route EVs to their destinations according to the most desirable route and (2) pre-empt traffic signals along the travelled route. The proposed strategy was developed to satisfy seven design requirements:

1. Route selection must be based on the anticipated travel time along a given route rather than travel distance.
2. Anticipated pre-emption conflicts along a given EV route must be considered to determine whether or not the route should be reviewed.
3. EV routes must be repeatedly reviewed and possibly updated while EVs travel through a road network.
4. All signalled intersections along a selected route need to be pre-empted for EV traversal.
5. When pre-empting at a given signalled intersection, the moment at which pre-emption should start must be based on the length of the vehicular queue blocking an approaching EV (instead of using a fixed pre-emption distance).
6. The adverse effect of pre-emption on non-EVs must be considered and reduced where possible.

7. When anticipated pre-emption conflicts are unavoidable, the conflict should be managed reactively.

The proposed strategy is encapsulated by a single primary algorithm called *proposedStrategy*(). This algorithm uses four secondary algorithms, which are *dijkstraInit*(), *preemptTiming*(), *simTrav*(), and *dijkstraRev*(). Both *dijkstraInit*() and *dijkstraRev*() use a tertiary algorithm called *calcCriteria*(). The execution order of these algorithms is shown in Figure 1.

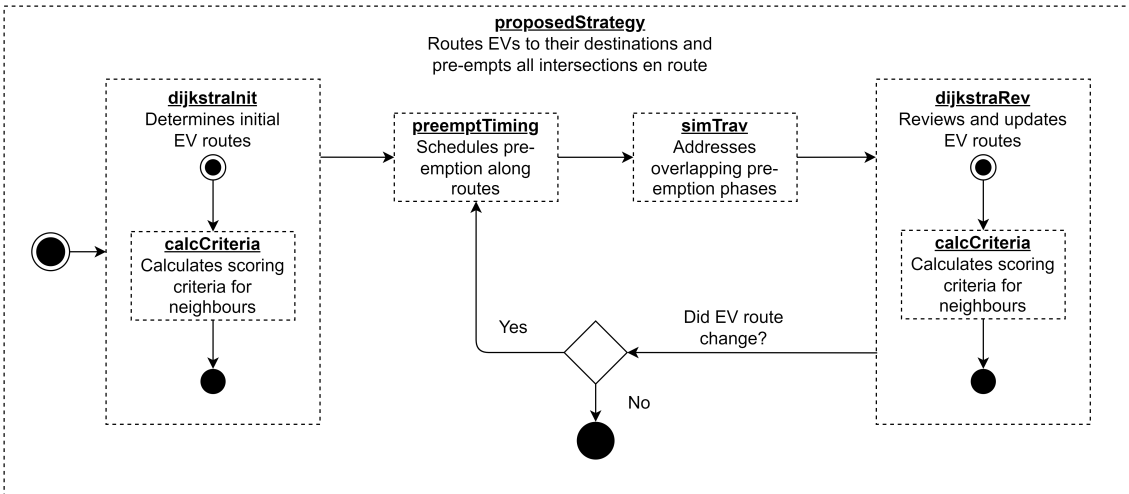


Figure 1: The execution order among the algorithms used within the proposed strategy.

The primary algorithm of the proposed strategy, *proposedStrategy*(), takes a road network as input, which it views as a graph (representing intersections as nodes and roads as links). (We describe the algorithm assuming more than one EV, but it applies to a single vehicle as well.) The positions of the EVs are initiated, and their starting and target nodes are retrieved, after which algorithm *dijkstraInit*() is called to calculate the initial routes of each EV. This algorithm (as well as *dijkstraRev*()) uses the classic Dijkstra-algorithm [23] – which was slightly modified – to assign initial routes to the EV(s). This initial assignment is based only on the distance-related travel time to EV destinations. An iterative route review process is triggered once initial routes are assigned to the EVs. Firstly, *preemptTiming*() determines the pre-emption timing for each EV at the nodes along their assigned route. Recall from Design requirement 5 that pre-emption should be timed based on the vehicular queue ahead of an approaching EV instead of using a fixed pre-emption distance. To do so, the proposed strategy needs to know when an EV will arrive at a given intersection, how long it is expected to require pre-emption at said intersection, and when this pre-emption phase should commence. According to Obrusník *et al.* [24], the time until pre-emption should be triggered (T_P) can be calculated using

$$T_P = T_A - t_{pr}, \tag{1}$$

where T_A refers to the time until an EV is expected to arrive at the stop line of a signalled intersection, and t_{pr} refers to the required duration of the pre-emption phase. It should be noted that this equation assumes that pre-emption is required until an EV arrives at the intersection. In some cases, pre-emption is permitted to terminate prior to this moment. In such cases, (1) is changed to

$$T_P = T_{prEnd} - t_{pr}, \tag{2}$$

where T_{prEnd} refers to the time until pre-emption is permitted to end. When determining the required duration of the pre-emption phase (t_{pr}), Shaaban *et al.* [20] and Qin & Khan [15] state that the relationship

$$t_{pr} \geq t_{so} + t_d + \text{SI} \tag{3}$$

must be obeyed where t_{so} refers to the time lost due to a signalled intersection having to switch its phase, t_d refers to the time required to discharge the vehicular queue ahead of an EV, and SI refers to an optional safety time interval. While the switchover time of the signalled intersection can be easily determined, calculating the time required for the queue to discharge is far more complex. A variety of approaches to doing so exist, but the approach proposed by Obrusník *et al.* [24] is chosen for use in the proposed strategy. Their approach was chosen, as it was analysed, tested using simulation and subjected to field experimentation in real traffic. The authors concluded that the results of their approach were promising. To see how t_d is calculated in the proposed strategy, refer to Obrusník *et al.* [24], as well as Akçelik *et al.* [25] and Akçelik & Besley [26].

After determining the pre-emption timings for all active EVs along their respective routes, the proposed strategy identifies nodes that two or more EVs will traverse, as these nodes are potential areas where pre-emption conflicts can occur. Nodes that multiple EVs will traverse are then passed to *simTrav*(), along with the pre-emption timing of each EV at these nodes. The *simTrav*() algorithm reviews the pre-emption timing parameters for all EVs that will pass through a given node. This involves attempting to assign a pre-emption phase capable of serving as many EVs as possible and adjusting the pre-emption timing of one or more EVs to award pre-emption on a first come, first served basis. Any anticipated delays caused to one or more EVs by the pre-emption of another are subsequently calculated. These delays are then used to review the route of each active EV. New routes are calculated for each EV using *dijkstraRev*(), potentially identifying a detour faster than remaining on the current route, given the expected delays caused by pre-emption conflicts. Once an acceptable detour is identified, the iterative route review process repeats until no route improvements can be found. In doing so, EVs that would initially have been involved in pre-emption conflict can be routed away from the conflict if a faster route presents itself.

As previously mentioned, both *djkstraInit*() and *djkstraRev*() use *calcCriteria*, which estimates the cost of visiting a given node in the road network. This cost is based on two criteria: the distance-related travel time to a given neighbouring node and the anticipated delay to an EV when visiting said node. These two criteria describe the total time an EV will take to traverse a given neighbouring node. The delay criterion is initialised to zero seconds and is updated when *calcCriteria* is called by djkstraRev(), indicating a review of the initial route of an EV. Re-routing an EV must be done cautiously, as only nodes along the initial route have been subjected to potential pre-emption. When considering re-routing an EV to a new node, the algorithm checks if there is sufficient time to pre-empt and clear the vehicular queue at that node. If not, the anticipated delay caused by the EV arriving at the uncleared queue is considered when calculating the cost of visiting a neighbouring node.

3.1.2 Reference strategy

The reference strategy developed is similar to the proposed strategy. Both strategies use the same algorithms that were previously discussed. The main difference is that the proposed strategy dynamically reviews and updates the routes assigned to EVs after pre-emption timing has been established to reduce expected delays caused by pre-emption conflicts. Another notable difference between these strategies is how pre-emption phases are selected. The proposed strategy prioritises pre-emption phases that allow the most traffic movements. This is done to enhance the vehicular flow through a given intersection during pre-emption. The reference strategy, on the other hand, allocates all-green pre-emption phases to approaching EVs, similar to some existing EVSP strategies, such as that proposed by Obrusník *et al.* [24]. By ensuring that the reference strategy is similar to the proposed strategy – with only the novel functionality being different between them – any performance differences can be attributed to this functionality.

3.2 Modelling the strategies

Three simulation models were constructed to investigate whether integrating EVSP and route selection can enable the proactive avoidance of pre-emption conflicts. These models were used to compare the proposed strategy to the reference strategy in a series of experimental runs. PTV VISSIM 2023 (a traffic simulation software) was selected for use in the study due to its ability to mimic traffic flow realistically and its component object model (COM) interface. The COM interface enables control over model agents based on the logic governed by the proposed or reference strategy. The proposed and reference strategies were implemented in MATLAB R2022b, from where they could be executed within PTV VISSIM through the COM interface. The way the COM interface links the PTV VISSIM and MATLAB components of the simulation models is illustrated in Figure 2.

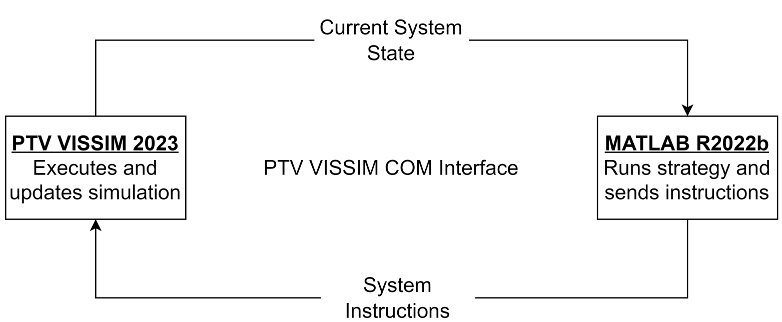


Figure 2: How the COM interface facilitates communication between PTV VISSIM and MATLAB.

Modelling road networks can typically be done by modelling an existing real-world road

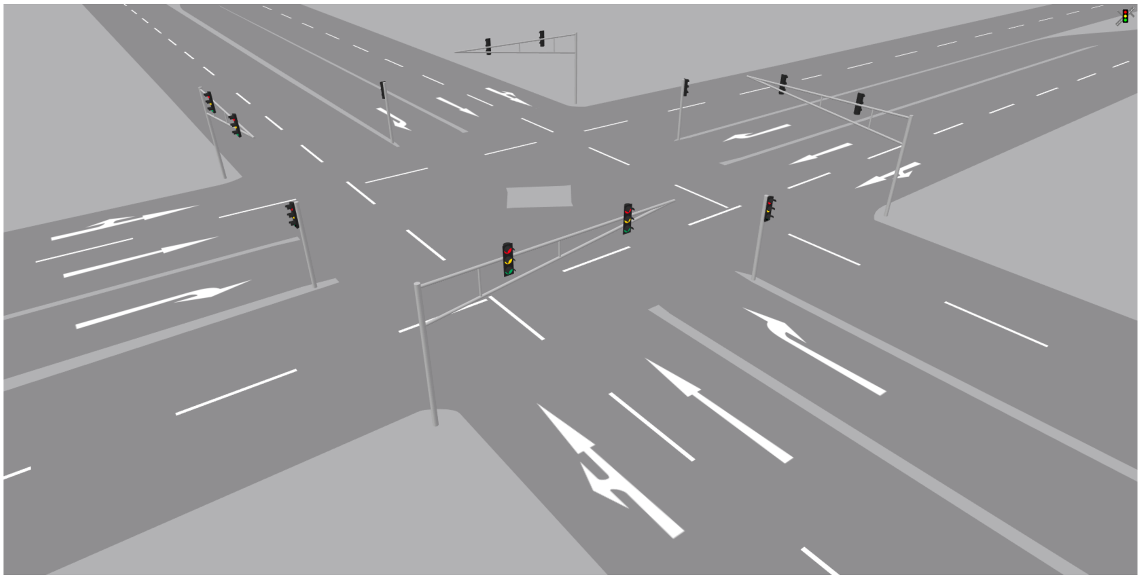


Figure 3: Example of a four-way intersection used in the simulation models.

network or by constructing hypothetical experimental road networks, as this study did. A 0.86 km x 0.7 km road network (referred to as Network 0) was modelled in VISSIM according to a grid layout, as this can be found in many urban areas. The road network has 14 edge nodes that serve as origin and destination locations. It also has 11 signalled intersections. An example of a four-way intersection used in the simulation models can be seen in Figure 3.

Each road link in the network has a speed limit of 60 km/h (with EVs being permitted to travel at their previously mentioned operating speed of 70 km/h) and consists of single lanes, except near an intersection approach where a right turn bay is included. A schematic plan view of Network 0 is shown in Figure 4. Network 0 was intended to be used as a simple base network from which progressively more complex networks were built. To compare the proposed and reference strategies in networks where roads have multiple lanes (which is expected to simplify overtaking), Network 0 was duplicated to become Network 1 (see Figure 5), in which each road has two lanes, except near an intersection approach where a right turn bay is included.

To investigate the robustness of the proposed strategy when subjected to road networks of different sizes, a 1.8 km x 0.79 km network (called Network 2) was modelled. Network 2, seen in Figure 6, is roughly double the size of Network 1, having 22 signalled intersections and 21 edge nodes. A fourth network (Network 3) was also modelled, roughly four times the size of Network 1 (1.77 km x 1.43 km). It has 44 signalled intersections and 27 edge nodes. Network 3 is shown in Figure 7. Networks 2 and 3 have the same grid layout used in Networks 0 and 1, the same speed limit, and two-lane roads. Most signalled intersections in the four road network models are four-way intersections, with Networks 2 and 3 having occasional three-way intersections. Every four-way intersection has 12 signal heads (except in Network 0, where it has four), while every three-way intersection has eight. A signal head refers to the part of a traffic signal that typically displays three coloured lights, specifically red, amber, and green. Each signalled intersection has its own signal controller that controls its signal heads.

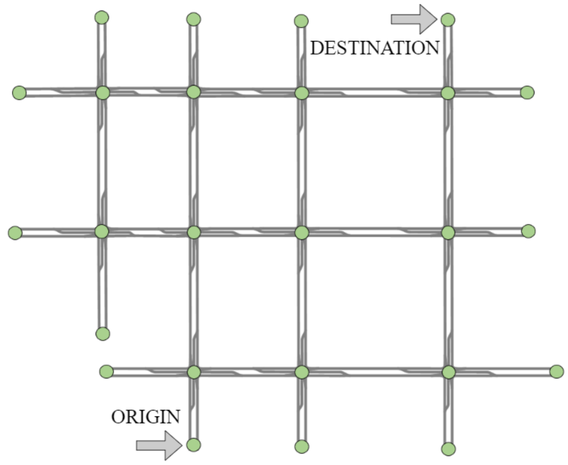


Figure 4: Network 0 containing 11 signalled intersections and single lane roads, with an example of origin and destination nodes used by an EV during a simulation run.

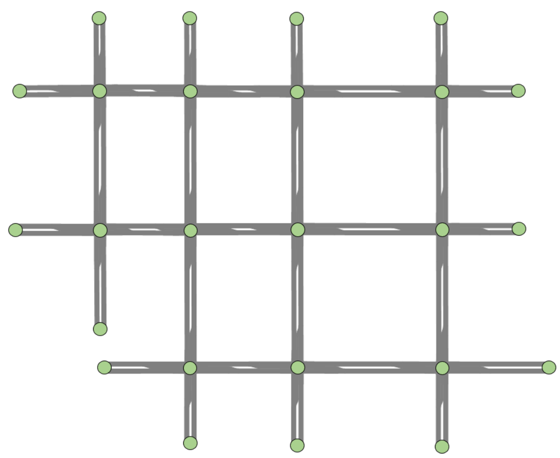


Figure 5: Network 1 containing 11 signalled intersections and double lane roads.

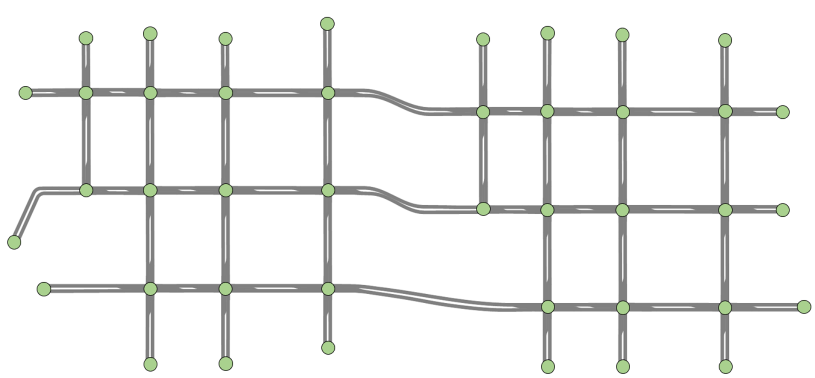


Figure 6: Network 2 containing 22 signalled intersections and double lane roads.

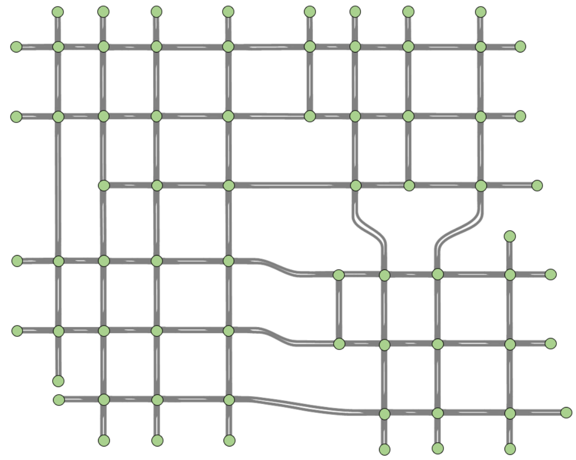


Figure 7: Network 3 containing 44 signalled intersections and double lane roads.

4 Experimentation and results

This section outlines the procedure to compare the proposed strategy to the reference strategy across the four road network models. The comparative experiments deployed varying numbers of EVs in each network, ranging from one to five. This enabled the robustness of the proposed strategy to be tested when the number of active EVs was varied. To ensure that EVs traversed each road network in various configurations, the edge nodes of each road network were divided into eight zones, each grouped according to four orientations along which EVs can traverse the network. This encompassed horizontal (H), vertical (V), and diagonal (D1 and D2) directions. An example of these zones is illustrated for Network 3 in Figure 8. The zone in the top left of the network, labled D1, consists of four possible start nodes, while the zone at the bottom right (also labled D1) is the corresponding destination set of nodes. An EV can thus start at a node in zone D1, top, left, and travel through the network to an assigned node in the bottom right. Travelling is not restricted to the general direction of left-to-right and top-to-bottom – an EV can, for example, start in the top right (D2) and travel to the bottom left of D2. The hatched regions indicate the associated start and end nodes of the four orientations.

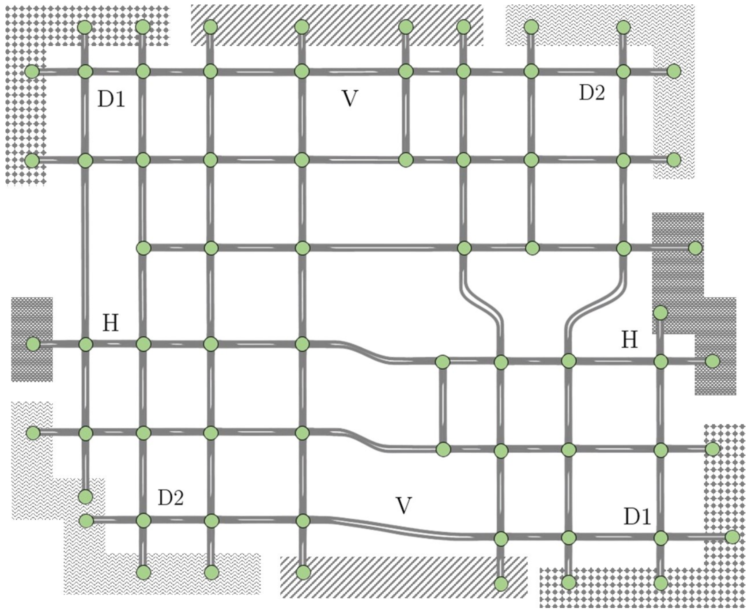


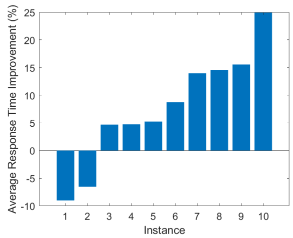
Figure 8: Network 3 experiment layout zones.

Table 1 served as a framework for structuring the allocation of layout zones to EVs. Consider four EVs being deployed in a network, with Combination 2 being allocated to these EVs. This means that two EVs need to traverse the network horizontally while the remaining two need to traverse it vertically. Note that none of the EVs can have the same pair of origin and destination nodes.

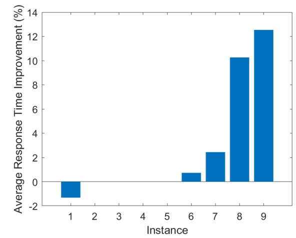
Table 1: Combinations of layout zones used in each road network for varying numbers of EVs.

Number of EVs	Combination 1	Combination 2	Combination 3	Combination 4
1	H	V	D1	D2
2	H-V	D1-D2	H-D1	V-D2
3	H-V-D1	H-V-D2	D1-D2-H	D1-D2-V
4	H-V-D1-D2	H-H-V-V	D1-D1-D2-D2	–
5	H-H-V-D1-D2	H-V-V-D1-D2	H-V-D1-D1-D2	H-V-D1-D2-D2

It follows from Table 1 that 19 unique layout combinations exist for each of the four road networks. Each layout combination was executed twice per road network for both the proposed and reference strategies – first when the network was close to its maximum capacity and then when it was at around 50% of its maximum capacity. This resulted in 38 comparative instances between the two strategies for each network (19 of which have high traffic levels, and the remaining 19 have relatively low levels). For each comparative instance, the response times of each EV (in this case, the time it took an EV to travel from its origin node to its destination node) were recorded and averaged, and these times allowed the reference and proposed strategies to be compared based on average EV response time. Note that each experimental run was first subjected to a warm-up period to ensure that the traffic conditions in the road network reached a steady state. The experiment runs



(a) Proactive avoidance attempted.



(b) Proactive avoidance not attempted.

Figure 9: Response time improvement for all instances in Network 1 when at maximum network capacity.

were executed on a 12-core Ryzen 9 5900X with 32GB 2133MHz RAM. After completing 152 comparative instances (38 per network), the results were analysed to determine how the proposed strategy compared to the reference strategy regarding average EV response time. The analysis reviewed how the results varied depending on specific variables, such as network size, network capacity, and the number of EVs that required service.

4.1 Varying network size at different network capacities

The results of the proposed strategy and reference strategy were first analysed to determine how they compare across Networks 0, 1, 2, and 3 (each having different sizes) when being at near-maximum capacity and then at 50% capacity. For each comparative instance between the proposed and reference strategies, the proposed strategy either re-routed one or more EVs to attempt proactive pre-emption conflict avoidance or maintained their initial routes. Distinguishing between instances in which the proposed strategy attempted to proactively avoid pre-emption conflicts and those where it did not provide insights into the proposed strategy's proactive and reactive conflict management capabilities. To analyse comparative instances, the response times of EVs in each instance were averaged for both the proposed strategy and reference strategy, after which the average response times could be compared. The goal was to empirically determine how often the proposed strategy resulted in average response time improvements and whether the joint improvements outweighed any delays.

To aid the analysis of results, the experimental results were plotted as bar graphs. An example is provided in Figure 9. Of the 19 comparative instances conducted in Network 1 when at near-maximum network capacity, the proposed strategy attempted to proactively avoid pre-emption conflicts in 10 instances (Figure 9a), while not doing so in nine instances (Figure 9b). Of the instances in which proactive pre-emption avoidance was attempted, the proposed strategy improved average EV response times in eight instances, with only two instances resulting in delays. When comparing the magnitude of the improved instances *versus* the delayed instances, the improvements were notably more significant than the delays. For the instances in which proactive pre-emption conflict avoidance was not attempted (but managed reactively), the proposed strategy improved average EV response times in four instances, with a single instance being delayed. Four instances resulted in the same average response time as the reference strategy. The magnitude of the improved instances is again larger than that of the delayed instances.

The remainder of the results (19 instances) are not presented in bar graph format but are instead condensed in table format to save space. Table 2 reports the results when comparing the two strategies in each road network at near-maximum capacity. For each network, the 19 comparative instances were categorised according to whether or not the proposed strategy proactively attempted to avoid pre-emption conflicts. For each case, the number of instances in which the proposed strategy improved average EV response times and the number of instances in which it caused response time delays are noted. It is also specified whether the magnitude of the improvements is larger than, smaller than, or almost equal to that of the delays.

Table 2: Results when comparing strategies with regard to varying network size at near-maximum capacity.

	Proactive Avoidance				Reactive Management			
Network	Total	Improvements	Delays	Improvement *vs* Delay Magnitude	Total	Improvements	Delays	Improvement *vs* Delay Magnitude
0	8	8	0	$>$	11	1	2	$>$
1	10	8	2	$>$	9	4	1	$>$
2	7	3	4	$>$	12	5	4	$\approx$
3	10	7	3	$>$	9	2	6	$<$

In instances where the proposed strategy proactively attempted to avoid one or more pre-emption conflicts, the average response time of EVs was visibly improved for Networks 0, 1 and 3 in most instances. However, the performance in Network 2 was worse, with longer average response times – rather than response time improvements – being recorded in more instances. Despite recording slightly more instances with response time delays, the magnitudes of the improved instances were notably larger than those of delayed instances.

For the instances in which the proposed strategy did not attempt to avoid pre-emption conflicts proactively, Network 0 recorded more delays than improvements. However, the improvement was much larger than the delays. While Network 1 had visible response time improvements, Network 2 suffered from response time delays almost as much as it experienced response time improvements, with their magnitudes being relatively similar. Network 3 had visibly poor response time results, with most instances being delays.

The response time delays reported here are likely caused by the fact that the proposed strategy does not allow all-green signal phases but rather those that allow the most movements. Because the networks are at maximum capacity, the likelihood of vehicles blocking the EV increased in the absence of an all-green signal. This could be observed in cases where vehicles wished to enter a right turn bay, blocking one of the two lanes of the through movement, restricting vehicular flow along the required movement of an EV, and causing an unforeseen delay. The comparative results for when the networks were at 50% capacity are reported next.

Table 3: Results when comparing strategies with regards to varying network size at 50% capacity.

	Proactive Avoidance				Reactive Management			
Network	Total	Improvements	Delays	Improvement *vs* Delay Magnitude	Total	Improvements	Delays	Improvement *vs* Delay Magnitude
0	10	6	3	>	9	1	0	>
1	9	5	4	>	10	4	0	>
2	5	1	3	<	14	7	4	>
3	7	4	3	<	12	7	3	>

When the networks were at half capacity, the proactive avoidance of pre-emption conflicts was attempted less often than when the networks were at maximum capacity. This is likely because shorter queues are expected to form ahead of an EV, meaning a route detour would be less appealing than if the queue had been longer. Networks 0 and 1 had visible response time improvements, while Networks 2 and 3 experienced more instances of response time delays than improvements.

Of instances in which proactive pre-emption conflict avoidance was not attempted, all three networks mostly showed response time improvements. Networks 0 and 1 had no response time delays, while a few delayed instances were present in the larger Networks 2 and 3. The delays that occurred under half-saturated conditions were fewer and less severe than unsaturated conditions. This is likely because there were fewer cases in which one of the lanes of a given road was blocked, allowing improved vehicular flow.

4.2 Varying network capacity regardless of network size

This subsection determines how the proposed strategy's ability to avoid pre-emption conflicts proactively is affected when considering different network capacities across all four modelled networks (regardless of their size and configuration). The average EV response time improvement results for both maximum network capacity and half network capacity are presented in Table 4.

Table 4: Results for all instances where proactive avoidance of pre-emption conflicts was attempted, based on network capacity.

Capacity	Total	Improvements	Delays	Improvement *vs* Delay Magnitude
Near-maximum	35	26	9	>
Half	31	16	13	≈

When considering all instances where pre-emption avoidance was attempted and analysing the response time improvements under different network capacities, changing routes to avoid pre-emption conflicts is more effective when networks are occupied at higher levels. As previously described, this is likely because vehicular queues are longer under near full capacity conditions. Longer queues lead to pre-emption conflicts, causing longer delays to

EVs. Avoiding these conflicts ensures better response time improvements than in networks at half capacity.

4.3 Varying number of emergency vehicles that require service

This subsection presents an analysis of how the proposed strategy compared to the reference strategy in all instances where the proposed strategy attempted to proactively avoid pre-emption conflicts (by re-routing one or more affected EVs) based on the number of EVs that required service. Because pre-emption conflicts can only occur when two or more EVs are present in each network, instances involving only one EV are excluded from this analysis. For each number of EVs, the analysis is first concerned with the number of instances in which proactive pre-emption avoidance was attempted and the response time improvements brought about after doing so. Table 5 reports the total number of instances where proactive pre-emption conflict avoidance was attempted by the proposed strategy for various EV numbers and how average EV response times were affected.

Table 5: Results when comparing strategies with regards to varying number of EVs that require service.

Number of EVs	Total	Improvements	Delays	Improvement *vs* Delay Magnitude
2	13	11	1	$>$
3	14	9	5	$>$
4	11	8	3	$>$
5	28	14	13	$\approx$

The number of instances in which an attempt was made to avoid pre-emption conflicts proactively is relatively constant for two, three, and four EVs. However, there is a noticeable increase in these instances when five EVs are present. This is due to the higher probability of pre-emption conflicts occurring with a greater number of EVs, resulting in more EVs being involved in such conflicts. The proposed strategy successfully avoids pre-emption conflicts when only two EVs are present in a network. It also performs well with three and four EVs, showing a similar number of instances with improved response times. In the case of five EVs, there are approximately equal instances of response time delays and improvements. This suggests that the proposed strategy is more effective when dealing with fewer than five EVs, possibly because fewer pre-emption conflicts occur. With more EVs, re-routing one EV away from an expected pre-emption conflict is more likely to create a new conflict elsewhere, diminishing the strategy's effectiveness.

4.4 Statistical analysis of overall results

Thus far, the results of comparing the proposed strategy to the reference strategy have been analysed regarding various factors, such as network size, network capacity, and number of EVs active in a network. The results of all 152 instances across all factors were jointly considered and statistically analysed to gain an overall picture of the ability of the proposed strategy to improve average EV response times. The results are presented in this subsection.

The proposed strategy attempted to avoid pre-emption conflicts in 66 instances proactively. Among these, average EV response times were improved in 42 instances, remained unchanged in two instances, and lengthened in 22 instances. This results in 44 of 66 instances being considered successes (67%). Statistical analysis showed that the strategy's expected success rate is in the interval 55.7% to 78.3% with 95% confidence.

There were 86 instances in which the proposed strategy did not proactively avoid pre-emption conflict. For these instances, the primary difference between the performance of the proposed and reference strategies was the number of movements that were allowed during each pre-emption phase. Of these instances, 35 had no change in average response time between the strategies. These instances are excluded from this analysis, as they represent cases where a pre-emption phase of one EV did not affect the response time of another. Only instances in which response time variations were noted are considered, a total of 51 instances. Of these, average EV response times improved in 31 instances (successes), while response times were lengthened in 20 instances, resulting in a success rate of 61%. Statistical analysis showed that the strategy's expected success rate is in the interval 47.6% to 74.4% with 95% confidence.

Lastly, all 152 instances in which the proposed strategy was compared to the reference strategy are considered, providing the best overall view of the proposed strategy's ability to reduce average EV response times, either by proactively avoiding pre-emption conflicts or by managing unavoidable conflicts reactively. The proposed strategy caused EV response times to either remain unchanged or improve in 110 instances (successes), with average response times lengthened in 42 instances. This results in a success rate of 72%. Statistical analysis showed that the confidence interval for this proportion, the strategy's overall expected success rate, is in the interval 64.9% to 79.1% with 95% confidence.

4.5 Execution time of proposed strategy

Because the proposed strategy is intended for use in emergencies where every second counts, the strategy should be able to execute in an acceptable time. If not, an EV could be delayed when awaiting routing instructions, which would counteract that which the proposed strategy seeks to avoid. The efficiency of the proposed strategy was therefore prioritised to ensure that redundant or inefficient steps are avoided. To review the execution time of the strategy, a test scenario was subsequently constructed using Network 3 (the largest network) and a total of five EVs that require service. The execution time of the proposed strategy is expected to be longer in larger networks containing multiple EVs that require service, as opposed to when a single EV requires service in a small network. The simulation run was executed, and it was determined that the proposed strategy could, on average, execute within a mere 1.5 seconds.

5 Conclusions and future work

The proposed strategy was compared to the reference strategy in various comparative instances. The comparison involved configuring variables such as network size, network capacity, and the number of active EVs that require service. The goal was to assess the strategy's robustness to changes in these variables and provide insight into its performance. While empirical observations suggest that the proposed strategy may not be entirely robust to the tested variables, it outperformed the reference strategy in most instances.

The proposed strategy demonstrated an ability to produce similar or shorter average EV response times compared to the reference strategy in most instances. The strategy's success is attributed to its proactive approach to avoiding anticipated pre-emption conflicts through re-routing EVs away from these conflicts and effectively managing unavoidable conflicts.

The following key findings were identified in this study:

- Proactive pre-emption conflict avoidance is possible by integrating emergency vehicle signal pre-emption and route selection.
- Integrating emergency vehicle signal pre-emption and route selection to proactively avoid pre-emption conflicts typically results in improvements to EV response times, making it a promising approach for future research.
- The emergency vehicle signal pre-emption and route selection strategy executes fast enough to be used as a real-time decision aid when EVs are called out to the scene of an emergency.

Recommendations that should be considered for future work include:

- Incorporating historical vehicle arrival rates in route selection and pre-emption scheduling.
- Defining queue lengths for individual lanes on multi-lane roads for more accurate queue length representation.
- Increasing the sample size by comparing the proposed strategy with the reference strategy in more instances.
- Testing the proposed strategy on larger, real-world road networks using simulation models.
- Integrating the proactive conflict avoidance approach of the proposed strategy into existing EVSP and route selection strategies.
- Modifying queue discharge equations to account for additional arrivals at the back of a queue in determining pre-emption start times.

References

[1] Zhang XQ, 2016, *The trends, promises and challenges of urbanisation in the world*, Habitat International, 54(3), 241–252.

[2] Ritchie H & Roser M, 2018, "Urbanization", *Our World in Data*, [Online], [Cited: 23 November 2023], Available: https://ourworldindata.org/urbanization.

[3] OECD and European Commission, 2020, *Cities in the World: A New Perspective on Urbanisation*, OECD Urban Studies, OECD Publishing, Paris.

[4] Lawrence O, 2022, *Engineering strategies towards the cataclysmic impacts of urbanisation on water resources sustainability*, World Journal of Advanced Engineering Technology and Sciences, 5(1), 15–24.

[5] Kodire V, Bhaskaran S & Vishwas H, 2016, *GPS and ZigBee based traffic signal preemption*, 2016 International Conference on Inventive Computation Technologies (ICICT), Coimbatore, India.

[6] Shelke M, Malhorta, A & Mahalle PN, 2019, *Fuzzy priority based intelligent traffic congestion control and emergency vehicle management using congestion-aware routing algorithm*, Journal of Ambient Intelligence and Humanized Computing.

[7] Bieker-Walz L & Behrisch M, 2019, *Modelling green waves for emergency vehicles using connected traffic data*, SUMO User Conference 2019, 62, 10–20.

[8] Mu H, Liu L, Song Y & Wang N, 2020, *Control Strategy of Signal Transition after Emergency Vehicle Signal Preemption*, Discrete Dynamics in Nature and Society, 2020, 1–11.

[9] Su H, Zhong Y.D, Dey B & Chakraborty A, 2021, *EMVLight: A Decentralized Reinforcement Learning Framework for Efficient Passage of Emergency Vehicles*, CoRR, abs/2109.05429.

[10] Oza P & Chantem T, 2021, *Timely and non-disruptive response of emergency vehicles: A real-time approach*, Proceedings of the 29th International Conference on Real-Time Networks and Systems, 192–203.

[11] Desai M, Rawani A & Loya MIM, 2019, *Reducing ambulance response time in emergency medical services: A literature review*, International Journal of Mechanical Engineering and Technology, 10(10), 85–96.

[12] Nguyen V.L, Hwang RH & Lin P.C, 2021, *Controllable path planning and traffic scheduling for emergency services in the internet of vehicles*, IEEE Transactions on Intelligent Transportation Systems, 23(8), 12399–12413.

[13] Humagain S, Sinha R, Lai E & Ranjitkar P, 2019, *A systematic review of route optimisation and pre-emption methods for emergency vehicles*, Transport Reviews, 40(1), 35–53.

[14] Kamble S & Kounte MR, 2022, *A survey on emergency vehicle pre-emption methods based on routing and scheduling*, International Journal of Computer Networks And Applications, 9(1), 60–71.

[15] Qin X & Khan AM, 2012, *Control strategies of traffic signal timing transition for emergency vehicle pre-emption*, Transportation Research Part C: Emerging Technologies, 25, 1–17.

[16] Wang Y, Wu Z, Yang X & Huang L, 2013, *Design and implementation of an emergency vehicle signal pre-emption system based on cooperative vehicle-infrastructure technology*, Advances in Mechanical Engineering, 5.

[17] Petrică BG, Ciobanu RI & Dobre C, 2021, *Automatic traffic light preemption for intelligent transportation systems*, 2021 20th International Symposium on Parallel and Distributed Computing (ISPDC), 1–8.

[18] Paruchuri V, 2017, *Adaptive pre-emption of traffic for emergency vehicles*, 2017 UKSim-AMSS 19th International Conference on Computer Modelling & Simulation (UKSim).

[19] Ajayi O, Bagula A, Chukwubueze & Maluleke H, 2020, *Priority based traffic pre-emption system for medical emergency vehicles in smart cities*, 2020 IEEE Symposium on Computers and Communications (ISCC), 1–7.

[20] Shaaban K, Khan MA, Hamila R & Ghanim M, 2019, *A strategy for emergency vehicle pre-emption and route selection*, Arabian Journal for Science and Engineering, 44, 8905–8913.

[21] Ogunwolu L, Sosimi A, Jagun O & Onyedikam C, 2019, *Optimal routing for automated emergency vehicle response for incident intervention in a traffic network*, Journal of Applied Sciences and Environmental Management, 22(12), 1941–1946.

[22] Cao M, Li VOK & Shuai Q, 2022, *A gain with no pain: Exploring intelligent traffic signal control for emergency vehicles*, IEEE Transactions on Intelligent Transportation Systems, 23(10), 17899–17909.

[23] Dijkstra EW, 1959, *A note on two problems in connexion with graphs*, Numerische Mathematik, 1, 269–271.

[24] Obrusík V, Herman I & Hurák Z, 2020, *Queue discharge-based emergency vehicle traffic signal preemption*, IFAC-PapersOnLine, 53(2), 14997–15002.

[25] Akçelik R, Besley M & Roper R, 1999, *Fundamental relationships for traffic flows at signalised intersections*, ARRB Transport Research Ltd. Research Report ARR 340.

[26] Akçelik R & Besley M, 2002, *Queue discharge flow and speed models for signalised intersections*, Transportation and Traffic Theory in the 21st Century, Emerald Group Publishing Limited, Leeds, 99–118.