Emergency Vehicle-Centered Traffic Signal Control in Intelligent Transportation Systems*

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***Abstract*— The fast response of an emergency vehicle, such as an ambulance, fire engine, police vehicle, etc., is crucial to the protection of human life and property. With the steady increase of vehicles, the road intersection, a most congestion-prone zone, has become a great challenge to the emergency vehicle's fast response despite its privilege of running a red light. To guarantee the safe, and fast pass of emergency vehicles stuck in congestion, an appropriate traffic signal control for emergency vehicle preemption is indispensable. In this work, we propose an emergency vehicle-centered traffic signal control, which focuses on the emergency vehicle's performance, while minimizing the negative impact on the traffic of conflicting directions. The proposed scheme can significantly decrease the emergency vehicle delay compared with the no preemption scheme (emergency vehicles have no priority), greatly reduce the impact on traffic of conflicting directions compared with the greedy preemption scheme (in which an emergency vehicle receives a green phase when it is detected to arrive at an intersection until it leaves), and notably lower the cost compared with the fuzzy logic-based scheme (which divides the real-time traffic conditions into several cases based on human knowledge and sets rules to control the signal accordingly).**

I. INTRODUCTION

An intersection on the road is prone to congestion and it becomes a hindrance for the fast pass of EMergency Vehicles (EMVs). For an EMV, such as ambulance, fire engine, police vehicle, etc., every second counts. In general, when such an EMV is to pass an intersection, it has the privilege of running a red light. However, due to blocked line-of-sight, running a red light may lead to a fatal accident between the EMV with other vehicles despite its sirens and flashing lights as shown in Fig. 1. In addition, at a congested intersection, an EMV can hardly exercise its privilege because it can be stuck somewhere away from the stop line as illustrated in Fig. 2.

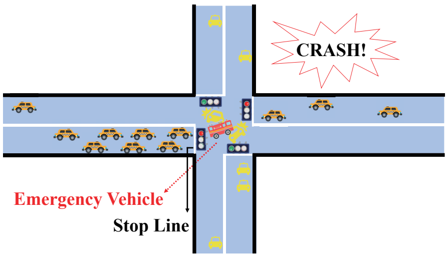

Fig. 1. A fatal accident due to running a red light.

Traffic signal control for EMV preemption is a common way to ensure its fast and safe passage at the intersection. Homaei *et al*. in [1] and Jha *et al*. in [2] give green signal to an EMV once it is detected at the intersection until it exits the intersection. This scheme (i.e. greedy preemption) guarantees the fast and safe passage of EMVs but will lead to great impact on non-EMV traffic as shown in Fig. 3.

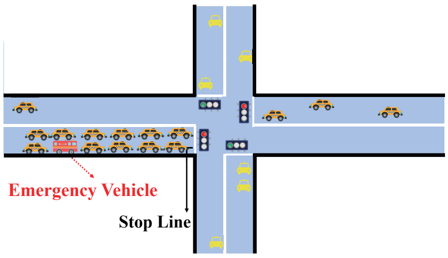

Fig. 2. Encountering congestion at an intersection.

Other work has tried to minimize such an impact without affecting the fast passage of EMVs. Louati *et al*. [3] design a multi-agent preemptive longest-queue-first system to facilitate the crossing of EMVs at the jammed intersection. Kapusta *et al*. [4] dynamically adapt the signal program of an intersection by using the EMV location and intersection queue length data so as to reduce the negative effects on the total travel time of all vehicles as well. Qin and Khan [5] adopt a relaxation method and a stepwise search strategy for EMV signal preemption for reducing EMV response time and minimizing its impact on the rest of the traffic. All these methods require real-time monitoring of queue length changes at all directions of the intersection.

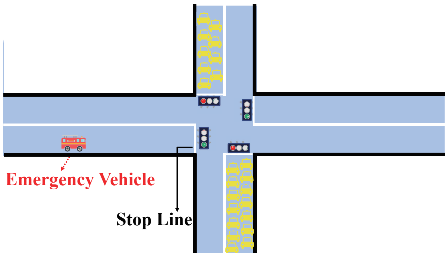

Fig. 3. Greedy preemption may lead to congestion of conflicting directions.

In addition to the queue length changes above, a fuzzy logic-based control is popular for traffic signal control [6], [7], [8], by using more real-time traffic information. Its chief idea is to divide the real-time traffic conditions (i.e., traffic speed, queue length, waiting time, congestion

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level, etc.) into several cases for controlling the signal based on human knowledge. Recently this fuzzy rule-based method has become a popular research direction for EMV preemption. Considering the current average traffic speed, congestion level, remaining time for the EMV's arrival, etc., Hajiebrahimi *et al*. in [9], Djahel *et al*. in [10] and Saeed *et al*. in [11] design fuzzy rule-based traffic control for enabling the fast emergency response while maintaining a minimal increase in congestion. Miletić *et al*. [12], by comparing the performance of fuzzy logic-based control and vehicle-tracking-and-queue-length based control [4], conclude that the former performs better. Obviously, we need to monitor the real-time traffic speed, queue length, waiting time of all vehicles and congestion level of each direction, etc., to provide sufficient information for the fuzzy logic-based control at an intersection, which will lead to a relatively cost.

In addition, the basic idea of the existing work is to achieve a tradeoff between the EMV performance and the impact on other vehicles, but the EMV performance may not be absolutely guaranteed. For example, when the non-EMV direction is very congested, the existing work can delay the time to give a green phase to the EMV direction, which will lower the average speed of the EMV.

However, the fast passage of the EMV is the most important. Even if the non-EMV direction is extremely congested, so long as the EMV performance is affected, like being forced to slow down or even stop, we must ensure that the EMV direction can get a green phase immediately.

Our contributions: In this work, we propose an EMV-centered scheme to control traffic signal for EMV preemption, with a reduced cost. In our EMV-centered scheme, the controller will only track the EMV performance when it is at the intersection rather than tracking the whole traffic condition at the intersection, thus greatly reducing the cost. In addition, with our proposed scheme, the EMV performance is always the paramount goal because it will timely control the traffic signal based on the real-time EMV performance to minimize the negative impact on non-EMV traffic without affecting the fast passage of EMVs. Based on both synthetic and real-world dataset, we conduct extensive simulations to validate the performance of our EMV-centered scheme by comparing with three other baseline methods.

II. SYSTEM MODEL

Let us consider an intersection as illustrated in Fig. 4. There are four approaching road segments from West (W), East (E), South (S) and North (N) directions, and each has three lanes. When an EMV arrives at the detection line (say 300-meter away from the centre of the intersection) from any direction, we consider it to be in the intersection. For better understanding, we define two green phases for the intersection as shown in Fig. 5. In Phase 1, the $W-E$ direction can either go straight or turn left or right and in Phase 2, the $N-S$ direction can either go straight or turn left or right. When an EMV arrives from the $W-E$ direction, we call it EMV direction and the $S-N$ direction as non-EMV direction. Please note that our model can easily extend to cases with more number of green phases and lanes at each road segment.

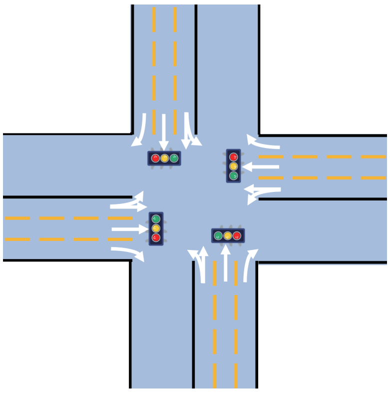
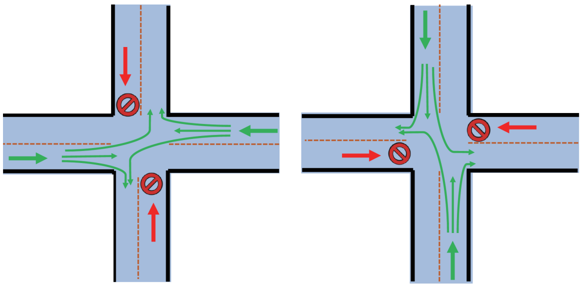


Fig. 4. System model.

When an emergency vehicle approaches the intersection, it will send its path information to the controller. Then the controller keeps measuring its speed and distance to the stop line as it moves on. Accordingly, the controller can control, in a timely fashion, the traffic signal to guide its fast pass while minimizing the negative impact on vehicles from the non-EMV direction.



Phase 1 **Phase 2**

Fig. 5. A two-phase intersection.

III. SCHEME DESIGN

From the introduction, we know that, with no signal control for EMV preemption, EMVs will suffer a long average duration at the intersection and the greedy signal preemption will lead to great impact on non-EMV traffic. Although existing work tries to minimize such an impact without affecting the fast passage of EMVs, the EMV performance may not be absolutely guaranteed. Our objective is to design an EMV-centered scheme, which regards the EMV performance as the paramount target and gives a green phase to the EMV direction whenever the EMV performance is detected to degrade or may do so.

We propose our algorithm based on the following insights. From the performance monitoring of an EMV, we can obtain, in a timely fashion, the impact of the current traffic condition on the EMV.

When the current signal for the EMV direction is red, even though there is no queue before the stop line of the EMV direction, the vehicle travelling at the head of the EMV direction will gradually slow down or stop, and this will propagate back, causing a stream of vehicles to slow down or even stop, which means that eventually the EMV will be affected, as shown in Fig. 6. When the traffic density of the EMV direction is heavy, the EMV will soon be affected and vice versa [13]. Therefore, by monitoring the speed change of an EMV, we can clearly see how the EMV performance is impacted due to the current traffic condition and accordingly guarantee its performance by giving the EMV direction a green phase in a timely fashion. In this way, with a relatively low cost (only monitoring the speed change of the EMV), we can dynamically assign appropriate green time of the non-EMV direction according to the real-time traffic density of the EMV direction, since the heavy traffic of the EMV direction means rapid forced slowdown of the EMV, and vice versa [13].

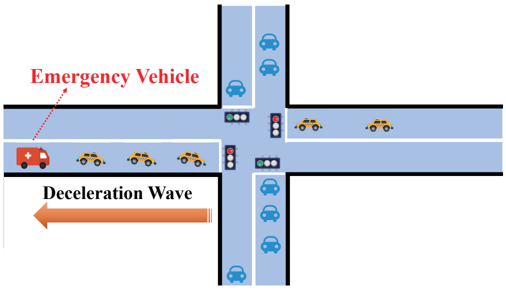


Fig. 6. Deceleration wave due to the red phase.

Moreover, to make sure the fast pass of the EMV, the controller also measures the delay of the EMV. The delay of a vehicle is an effective expression to reflect the relative speed of a vehicle compared with the speed limit of the lane [14]. In this work, we define the delay of the EMV as follows.

$$EMV\,Delay = 1 - \frac{EMV\,Speed}{Speed\,Limit}. \tag{1}$$

Obviously, the lower the EMV delay, the higher the EMV speed. After a certain time period T since the EMV enters the intersection, if the EMV delay is still higher than the given value d_{max}, where $d_{\max} \in [0,1]$, we can determine that the EMV direction is so crowded that the EMV cannot get its reasonable speed after T, and then we will give a green phase to the EMV direction immediately.

Besides, when the EMV is close to the stop line, i.e., a distance within D_{min} from the stop line, we will also give a green phase to the EMV direction immediately. In this way, we can ensure the green signal for the EMV when it reaches the stop line since there is usually a few seconds' duration of yellow light between the signal switch. At the same time, this action will also discharge the potential queue length at the stop line. Therefore, the EMV can pass the intersection without stopping or being slowed down.

In addition, if the EMV fails to leave the intersection within the period of T_{max}, green phase for the EMV intersection will be given immediately. This operation can further guarantee that the EMV can pass the intersection within the reasonable duration of time.

Algorithm 1 EMV-Centered Scheme (EMVCS)

```
After detecting the arrival of an EMV at an intersection, the controller keeps measuring the speed, delay, distance from the stop line and stay time of the EMV
At each second before the EMV's departure, run EMVCS()
function EMVCS()
    if EMV speed $< 0.1m/s$ then
        Give a green phase to the EMV direction
    end if
    if EMV speed decrease of 1s $> \Delta S_{\max}$ then
        Give a green phase to the EMV direction
    end if
    if EMV distance to stop line $<= D_{min}$ then
        Give a green phase to the EMV direction
    end if
    if $T <$ EMV stay time $< T_{max}$ then
        Calculate EMV delay as Eq. (1)
        if EMV delay $> d_{max}$ then
            Give a green phase to the EMV direction
        end if
    end if
    if EMV stay time $>= T_{max}$ then
        Give a green phase to the EMV direction
    end if
end function
```

Algorithm 1 describes the EMV-centered scheme and we can set the parameters of $\Delta S_{\max}$, T, d_{max}, D_{min} and T_{max} according to the conditions of different intersections, such as speed limit and so on. We assume the traffic controller and EMVs can communicate well through road-side unit as in previous work [15].

IV. PERFORMANCE EVALUATION

In this section, we evaluate with a few tests how our proposed method performs against three baseline methods, i.e., no preemption scheme [16], [17], greedy preemption scheme [1], [2] and fuzzy logic-based scheme [10], [12]. We first assess our performance in a synthetic dataset, which consists of four extreme traffic flow cases. Then, we run our experiments based on datasets at a real-world intersection in Cologne, Germany.

A. Simulation Setup

We consider an isolated intersection as illustrated in Fig. 4. The experiments are conducted on a simulation platform Simulation of Urban MObility (SUMO). SUMO provides flexible APIs for road network design, traffic volume simulation and traffic signal control. Specifically, SUMO can control the traffic flow according to the given policy of traffic signal.

In all simulations, if there is no EMV in the system, the traffic signal stays under a fixed-time control, which is of wide use and low cost. Other baseline methods and our proposed method will take over the traffic control signal when an EMV is detected at the intersection until it leaves. Other parameters of our EMV-centered scheme are shown in Table I.

TABLE I

PARAMETERS OF EMV-CENTERED SCHEME

Parameter	Value
$\Delta S_{\max}$	4.5 m/s
T	10 s
d_{max}	0.5
D_{min}	50 m
T_{max}	23 s
Speed limit	20 m/s

We will evaluate the performance of different schemes with the following metrics.

1) Duration of an emergency vehicle: the total time (in seconds) that an EMV has stayed at the intersection before it leaves.

2) Stop count: the total number of stops that an EMV has encountered at the intersection before it leaves. In our simulations, when the EMV speed is less than 0.1 m/s at a certain second or the speed decrease of an EMV within one second is greater than $\Delta S_{\max}$ in Table I (slamming on the brakes), one stop is counted.

3) Queue length of non-EMV direction: the total number of queueing vehicles of all the lanes in the non-EMV direction. For example, if an EMV arrives from W to E or from E to W, the non-EMV direction is the $S-N$ direction (both S to N and N to S included), and vice versa. If the EMV speed is less than 0.1 m/s, we consider it as waiting.

4) Waiting time of non-EMV direction: the total waiting time (in seconds) of queueing vehicles of all the lanes in the non-EMV direction. Similar to much previous work (e.g., [14]), the waiting time of an queueing vehicle i at time $t+1$ is calculated as follows.

$$W_i(t+1) = \begin{cases} W_i(t) & speed\,of\,i < 0.1m/s \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

As shown in Eq. (2), the waiting time of a vehicle is reset to zero every time it starts to move.

5) Throughput: the average total number of vehicles that leave the intersection every minute.

B. Performance under Synthetic Dataset

In the first part of our experiment, synthetic data is used with four traffic flow settings: heavy traffic flow along both directions (Case A), light traffic flow along both directions (Case B), heavy traffic flow along the EMV direction and light traffic flow along the non-EMV direction (Case C), and light traffic flow along the EMV direction and heavy traffic flow along the non-EMV direction (Case D). Other parameters are shown in Table II.

Owing to the symmetry of the synthetic traffic flow from the four directions, we suppose the EMVs are from W to E in the simulations on the synthetic dataset. The four cases represent four typical traffic settings for EMV preemption, in which different baseline methods will deliver different performance.

TABLE II

FOUR CASES OF TESTING ON SYNTHETIC TRAFFIC DATA

Case	Direction	Traffic flow (vehicles/s)	Duration (s)
A	$W-E$	0.3	108000
	$S-N$	0.3	
B	$W-E$	0.04	108000
	$S-N$	0.04	
C	$W-E$	0.3	108000
	$S-N$	0.04	
D	$W-E$	0.04	108000
	$S-N$	0.3	

First, we will show the EMV performance (including the duration and number of stops) under different schemes. EMV duration is the total travel time that an EMV spends in the intersection and stop count is the total number of stops of an EMV when it is at an intersection.

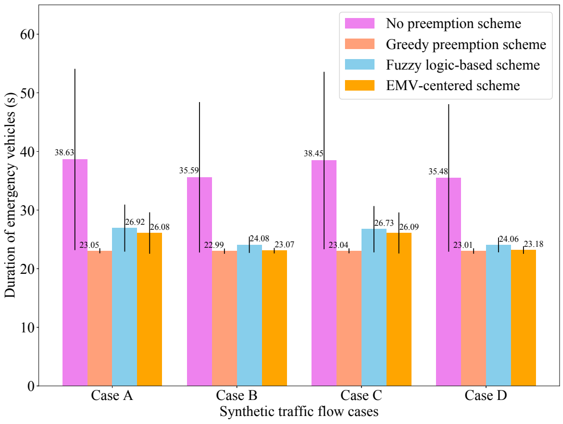
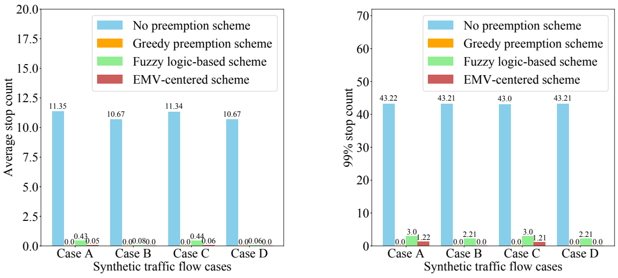


Fig. 7. Duration of emergency vehicles of four synthetic test cases.

As illustrated in Fig. 7, the greedy preemption scheme achieves the shortest average duration of EMVs and the no preemption scheme suffers the longest average duration of EMVs in the four test cases. The average duration of the fuzzy logic-based and our EMV-centered schemes is a little longer than that of the greedy preemption scheme. It can be noted that our scheme achieves a shorter average duration than the fuzzy logic-based scheme in all four cases. It can also be observed that the greedy preemption scheme achieves the most stable performance in terms of duration (smallest standard deviation). Besides, the duration performance of our scheme is more stable than both the fuzzy logic-based and no preemption schemes in the four cases above.

From Fig. 8 (a) and (b), we can find that, for the no preemption scheme, the numbers of stops in terms of both



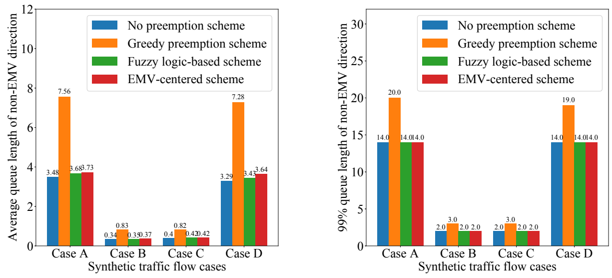
(a) Average stop count (b) 99% stop count

Fig. 8. Stop count performance of four test cases for both average and 99 percentile values.

average and 99 percentile values are much bigger than the other three schemes. Our EMV-centered scheme achieves the same (in Cases B and D) or almost the same (in Cases A and C) number of stops as the greedy preemption scheme in both average and 99 percentile values. Compared with the fuzzy logic-based scheme, our scheme obtains better performance in terms of stop counts in all four cases.

Overall, from Fig. 7 and Fig. 8 (a) and (b), one can see that the EMV performance of our EMV-centered scheme is almost the same (especially in Cases B and D) as the greedy preemption scheme, better than the fuzzy logic-based scheme and much better than the no preemption scheme.

Then, we will illustrate the performance (including queue length, waiting time and throughput) of non-EMV traffic under different schemes.

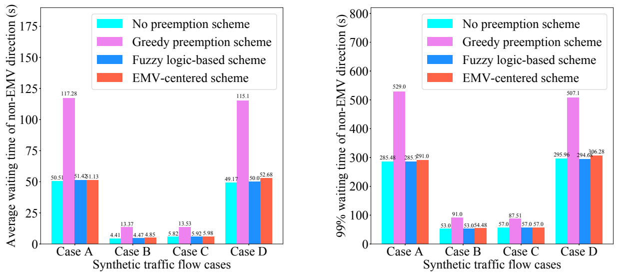


(a) Average queue length (b) 99% queue length

Fig. 9. Queue length of non-EMV directions for both average and 99 percentile values.

As illustrated in Fig. 9 and Fig. 10, the greedy preemption scheme suffers the longest queue length and waiting time of the non-EMV direction since it occupies too much green time. Compared with the no preemption scheme, the fuzzy logic-based and our EMV-centered schemes obtain longer queue length and waiting time. The queue length and waiting time of our scheme is a little longer than the fuzzy logic-based scheme.

Overall, the greedy preemption scheme achieves the shortest duration and smallest number of stops of EMVs as shown in Fig. 7 and Fig. 8, but it suffers the longest queue length and waiting time of the non-EMV direction as shown in Fig. 9 and Fig. 10. With a little longer queue length and waiting time of the non-EMV direction, the fuzzy logic-based and our EMV-centered schemes achieve much better duration and number of stops of EMVs than the no preemption scheme. It can also be noted that, compared with the fuzzy logic-based scheme, our EMV-centered scheme achieves better EMV performance with a minor impact on non-EMV traffic.



(a) Average waiting time (b) 99% waiting time

Fig. 10. Waiting time of non-EMV directions for both average and 99 percentile values.

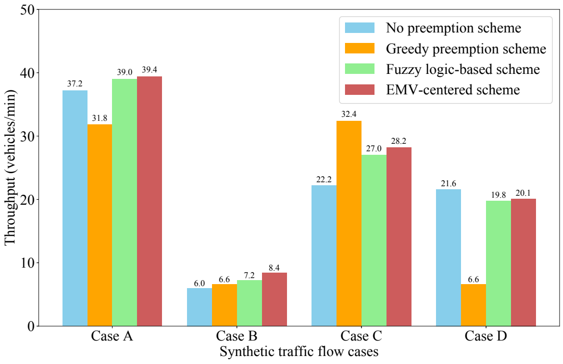


Fig. 11. Throughput of the intersection during the pass of an emergency vehicle.

From Fig. 11 one can see that, our scheme achieves the biggest throughput in Cases A and B where the traffic flow of both directions is balanced. Besides, in Case C, where the traffic flow of the EMV direction is heavy and that of the non-EMV direction is light, the greedy preemption scheme achieves the biggest throughput since it assigns more green time to the EMV direction, which has heavy traffic flow in Case C. In Case D, where the traffic flow of EMV direction is light and that of the non-EMV direction is heavy, the no preemption scheme achieves the best throughput since it occupies no green time of the non-EMV direction. It is also noted that in Cases C and D, our scheme achieves the second biggest throughput.

C. *Performance under a Real-world Intersection*

In this part, we will test different schemes with the vehicular mobility dataset of Cologne, Germany. This dateset is gathered every second in a typical working day in Cologne covering a region of 400 square kilometers, and comprises more than 700,000 individual vehicle trips [18].

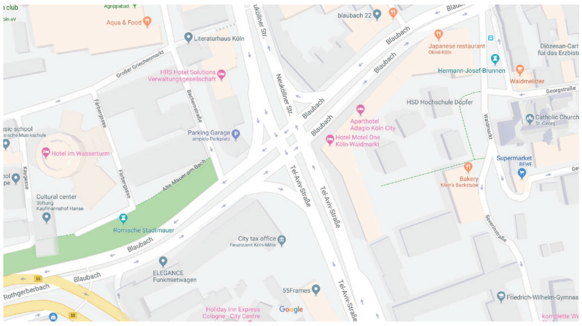


Fig. 12. The real-world intersection.

We choose a typical four-way intersection as shown in Fig. 12. It is at the cross point of major roads for both $W-E$ and $S-N$ directions and prone to daily recurring congestion (especially during morning and afternoon peak hours), and therefore suitable as a real traffic case to test the preemptive control. From the original dataset, the trajectories of vehicles are recorded every second when they pass through this intersection. We use the number of passing vehicles as the experimental traffic volume.

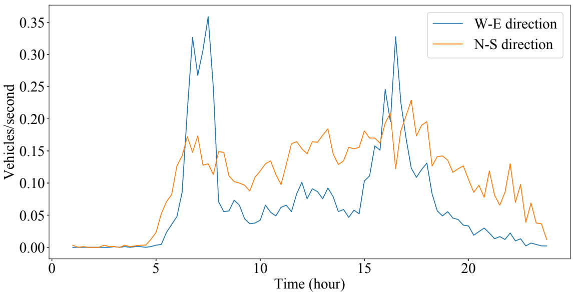


Fig. 13. Traffic flow at the selected intersection.

From Fig. 13, one can see that the traffic flow from different directions is dynamically changing in the real world and that, at such peak hours as 06:30 - 08:30 am and 16:00 - 18:00 pm, the intersection is jammed and may not be able to allow a rapid passage of an EMV. In the following simulations we show the results for both peak and non-peak hours.

The simulation duration is $10 \times 24h$ (i.e., 10 days) and an EMV can randomly arrive from any direction and its arrival is generated by Poisson distribution with an average arrival rate of 1 EMV/30min.

Overall, from all the following figures, one can see that the performance comparison of three all schemes (including ours) is similar to that in the synthetic dataset. That is, in the real-world dynamic traffic flow, our method is effective in minimizing the impact on non-EMV traffic (compared with the greedy preemption scheme) and greatly improves the EMV's performance (compared with the no preemption scheme) at a reduced cost (compared with the fuzzy logic-based scheme).

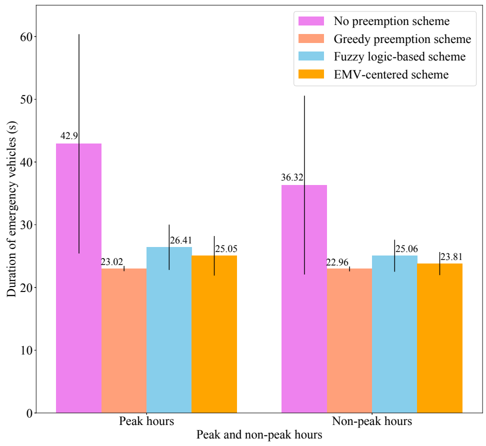
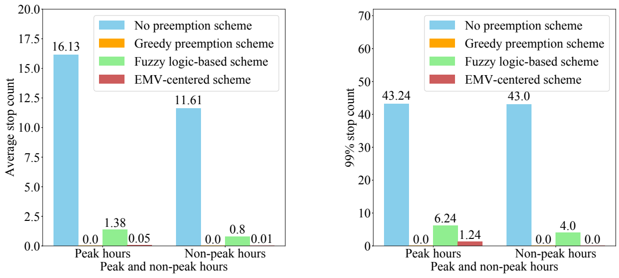


Fig. 14. Duration of emergency vehicles at a real-world intersection.

One can observe that, compared with the results at non-peak hours, the EMV performance (including duration in Fig. 14 and number of stops in Fig. 15) of the no preemption scheme becomes much worse at peak hours due to the increased traffic flow.



(a) Average stop count

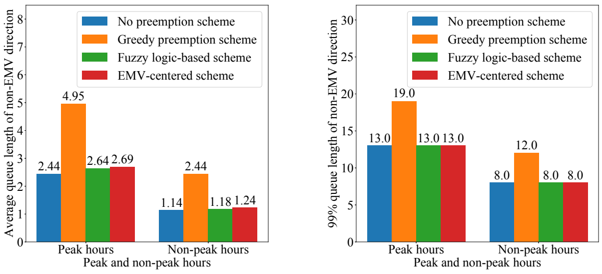
(b) 99% stop count

Fig. 15. Stop count performance for both average and 99 percentile values at a real-world intersection.

Although the greedy preemption scheme maintains a good EMV performance (including duration in Fig. 14 and number of stops in Fig. 15) even at peak hours, it occupies too much green time, thus resulting in much longer queue length (Fig. 16) and waiting time (Fig. 17) of the non-EMV direction.

For the fuzzy logic-based scheme, compared with the results at non-peak hours, performance over all metrics (Fig. 14, Fig. 15, Fig. 16, and Fig. 17), except for throughput (Fig. 18), degrades at peak hours. Due to the heavy traffic flow, the throughput of each scheme gets bigger at peak hours.

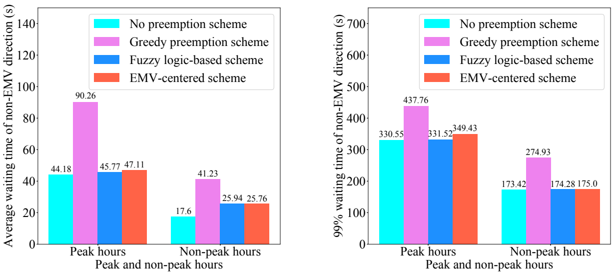
It can also be noted that, at both peak and non-peak hours, our EMV-centered scheme maintains a better EMV performance (including duration shown in Fig. 14 and



(a) Average queue length (b) 99% queue length

Fig. 16. Queue length of non-EMV directions for both average and 99 percentile values at a real-world intersection.

number of stops shown in Fig. 15) than the fuzzy logic-based scheme with a little longer queue length (Fig. 16) and waiting time (Fig. 17) of the non-EMV direction.



(a) Average waiting time (b) 99% waiting time

Fig. 17. Waiting time of non-EMV directions for both average and 99 percentile values at a real-world intersection.

From Fig. 18 one can observe that our scheme achieves the biggest throughput at both peak and non-peak hours.

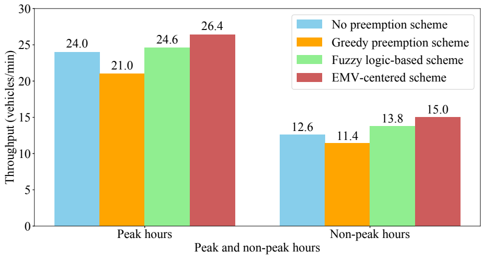


Fig. 18. Throughput of the intersection during the pass of an emergency vehicle at a real-world intersection.

V. CONCLUSION

In this work, we propose an EMV-centered scheme, which focuses just on the EMV's performance (speed change, delay, distance from stop line and stay time included), to guarantee its fast pass and notably minimize the impact on non-EMV traffic at a greatly reduced cost. We conduct comprehensive simulations to assess the performance of our EMV-centered scheme based on synthetic and real-world datasets. The results indicate that the proposed scheme can significantly decrease the EMV duration compared with the no preemption scheme, greatly reduce the impact on non-EMV traffic compared with the greedy preemption scheme, and notably lower the cost compared with the fuzzy logic-based scheme.

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