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Traffic Signal Coordination for Emergency Vehicles

Wenwen Kang, Gang Xiong, Yisheng Lv, Xisong Dong, Fenghua Zhu, Qingjie Kong

Abstract— **Reducing travel time of emergency vehicles (EVs) has a potential in significant savings of life and property. Integrating modern intelligent transportation system (ITS) with EV signal preemption seems to be a solution. But existing EV signal preemption systems often break the current signal coordination and impact a lot on the normal traffic streams. In this paper we propose an emergency vehicle signal coordination (EVSC) approach, which is intended to provide "green wave" for EVs. Traffic simulations are conducted along an emergency corridor with 8 intersections in Qingdao, China. Multiple traffic measurements are compared between simulation outputs with and without EVSC operation. The result indicates that the proposed approach can reduce EV travel time by 26.9% without too much negative impact on the normal traffic streams.**

I. Introduction

With increasing complexity of modern city, more and more kinds of incidents, including fires, crimes or sudden disease attacks, could happen at any time anywhere in the city. Emergency vehicles like firefighting trucks, police cars or ambulances are required to arrive at the incident scene as soon as possible. Time is the critical factor determining if an emergency operation will be successful. It's great challenge for emergency vehicles to get to the incident scene in a safe manner quickly, especially when traffic becomes increasingly heavy and traffic pattern grows more complex in modern cities.

Researchers and traffic engineers have developed several traffic signal priority strategies for EVs to pass intersections quickly and safely. Different kinds of emergency vehicle signal preemption (EVSP) systems are utilized at signalized intersections to provide prior pass for EVs. Usually emergency vehicle detectors are installed a distance upstream to the intersection. On detection of an emergency vehicle, the detector sends an emergency priority request to the traffic signal controller. Once the controller receives the request, it determines (conditionally or unconditionally) how the request will be responded. If the priority request is approved, the controller terminates the normal signal operation as soon as the minimum green time is elapsed, and changes its settings to grant the emergency priority request. After a signal received indicating that the emergency vehicle has passed the intersection, the controller takes the transition strategy to recover from preemption phase to normal signal operation. In coordinated systems, the transition is finished as soon as the controller restores the proper signal offset value again.

Existing research indicates that EVSP operation has a great potential in facilitating emergency vehicles' arrive at the incident scene in time. Paniati and Amoni report that travel time saved by EVSP systems varies from about 14% to 25% [1]. Kamalanathsharma and Hancock show in their work that time saving can reach up to 31% compared to cases without emergency vehicle preemption [2].

In spite of its great effectiveness in saving emergency vehicles' travel time, preemption based emergency vehicle signal priority has its disadvantages in practice. Since each time an EV approaching the intersection, a preemption request has to be granted. This interrupts the normal traffic streams too frequently. The other problem is more important when the existing traffic signal settings are coordinated along the emergency corridor. Since EVSP needs to extend or shorten phase length, insert phase or change phase order, the existing signal coordination no longer holds, which will introduce further negative impacts on the normal traffic streams. Yun et al. conclude that a single EV preemption can cause a significant disruption of 24%-28% increase in coordinated arterial travel times [3]. Nelson and Bullock observe an increase in the average travel time of about 20-30 seconds along a four-intersection arterial [4]. The overall traffic delay is reported to increase by range from 4% to 58% as a result of traditional EVP methods. And the delay could be longer during peak hours [5][6].

As to the problems documented above, this paper attempts to use the EVSC approach, which provides "green wave" for EVs to promote their pass through intersections. The "green wave" is achieved by signal coordination setting. The method proposed in this paper is easily implementable and cost efficient. It causes minimum negative impact on normal traffic streams and maintains signal coordination at the same time. The remainder of this paper is organized as follows. Section II describes the EVSC approach proposed in this paper, including the method background. Section III validates the proposed approach by conducting and comparing some microscopic traffic simulations. And finally section IV ends with some conclusions and recommendations for future work in improving the effectiveness of the proposed approach.

II. Methodology

A. Background

The core idea of the EVSC approach is to provide "green wave" for EVs to pass intersections continuously along the emergency corridor. A green wave is a kind of traffic signal operation that allows continuous movement of vehicles through successive intersections. The driver encounters green

Wenwen Kang and Gang Xiong are with the Qingdao Academy of Intelligent Industries, Qingdao, Shandong, 266109, China. Prof. Gang Xiong is the corresponding author (email: gang.xiong@ia.ac.cn).

Fenghua Zhu and Xisong Dong are with the Beijing Engineering Research Center of Intelligent Systems and Technology, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China.

Qingjie Kong and Yisheng Lv are with the Cloud Computing Center, Chinese Academy of Sciences, Songshan Lake, Dongguan, 523808, China.

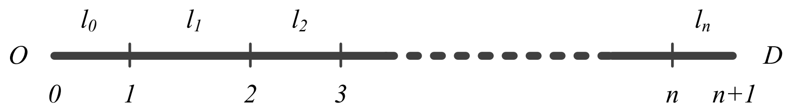

Figure 1. Schematic representation of an emergency corridor with n intersections.

light each time he approaches the intersection, seems like a wave of green lights travels along the road at certain speed. Green wave is achieved by signal coordination along the route. This kind of coordination operation of traffic lights has many advantages [7]: 1) higher level of traffic service in terms of higher through speed and fewer stops; 2) more smooth traffic flows; 3) more uniform vehicle speeds; 4) fewer accidents; 5) greater obedience to the signal commands; and 6) promoted attraction of arterial streets. It is expected that applying signal coordination operation for EVs along the emergency corridor can also benefit from these advantages.

Since it has great potential benefits, signal coordination study has attracted many researchers' attention. It has been improved a lot since Gartner and his colleagues proposed a multi-band approach to calculate optimal traffic signal coordination setting along an arterial [8]. In this research, they improve the previous bandwidth-based models by taking the actual traffic volumes into consideration. Multiple green bandwidths are developed for each directional road section instead of a uniform bandwidth in each direction along the arterial. Mixed-integer linear programming is used to solve the optimization problem. Later more researchers make their efforts in this area. Girianna and Benekohal formulate the signal coordination model as a dynamic optimization problem and solve it using the Genetic Algorithms (GA) [9]. Tian and Urbanik use a system partition technique, which divides the large arterial into subsystems with three to five signals. A heuristic approach is proposed to find the optimal solution [10]. Experiences obtained and lessons learned from previous practice and research are discussed in [11]. These guidelines reduce the time and effort needed in solution tuning, thus improve the efficiency and effectiveness in signal coordination design. Based on these brilliant research, the arterial-based approach is then extended to grid network case by other researchers [12][13][14].

Since the problem in this paper is to provide green wave for EVs along a certain emergency corridor instead of the whole traffic streams along an arterial. The approach proposed in this paper is different from theirs in two ways:

1) We only need to provide one-way green wave for EVs instead of two-way green waves as existing signal coordination research did.

2) Only through phases need to be coordinated in traditional arterial-based signal coordination. But in the EVSC case, left turn and right turn phases should also be coordinated since any kinds of movements could happen at the intersections along the emergency corridor.

Traffic signals tend to group vehicles into "platoon" with more uniform headways than would otherwise occur. This is called the "platooning effect" [8]. It is good choice for EV drivers not to stay too close to the head or tail of the platoon. If staying too close to the platoon head, it has a greater probability that the driver has to make a full stop at the intersection waiting for existing queue to clear. The cleared queue will act as the new head of the platoon. As a result, if staying too close to the platoon tail the vehicle maybe crowded out of the current platoon, failing in pass the intersection continuously. So it is the best choice for EVs to stay in the middle of a platoon. This goal can be achieved by adjusting coordinated signal offsets such that it is just half the green phase each time EV passes the intersection.

B. Signal coordination for emergency vehicles

Assume an emergency corridor with n signalized intersections indexed by 1 to n respectively. In addition, the origin is indexed by 0 and destination by $(n+1)$ (see Fig. 1). S_i denotes the signal at node (intersection) i where $i=1,\cdots,n$. We define the following notations:

v expected travel speed of the emergency vehicle

l_i link length starting from node i to node $i+1$, where $i=0,\cdots,n$. Note that l_0 means the distance from the origin to the first signal, and l_n means the distance from the last signal to the destination.

M_i movement to take at signal i to get to the destination. Not like arterial-based signal coordination where only through movements need to be taken into consideration, in EVSC cases left turn and right turn movements also need to be coordinated. $M_i \in \{L, R, T\}$ where L for left turn, R for right turn, and T for through movement.

c signal cycle length. It is expected that the optimal cycle length is given.

g_i green time with respect to the specific movement M_i at node i.

r_i red time with respect to the specific movement M_i at node i. It is expected that this is given, thus g_i is also given.

φ_i signal offset at node i relative to that at node i-1, where $i=1,\cdots,n$. The value of φ_i is calculated as the time difference between the starts of two signal cycles at node i and node i-1 which are immediately prior to the EV's passing time. Define $\varphi_0=0$.

Δ_i midpoint offset of g_{i-1} and g_i inner a cycle, where $i=2,\cdots,n$.

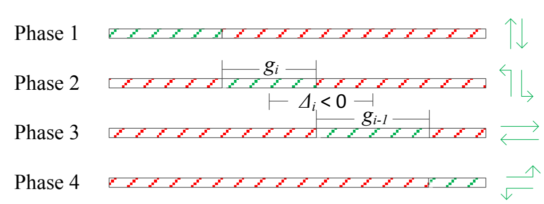

Figure 2. Value of Δ_i can be either positive or negative.

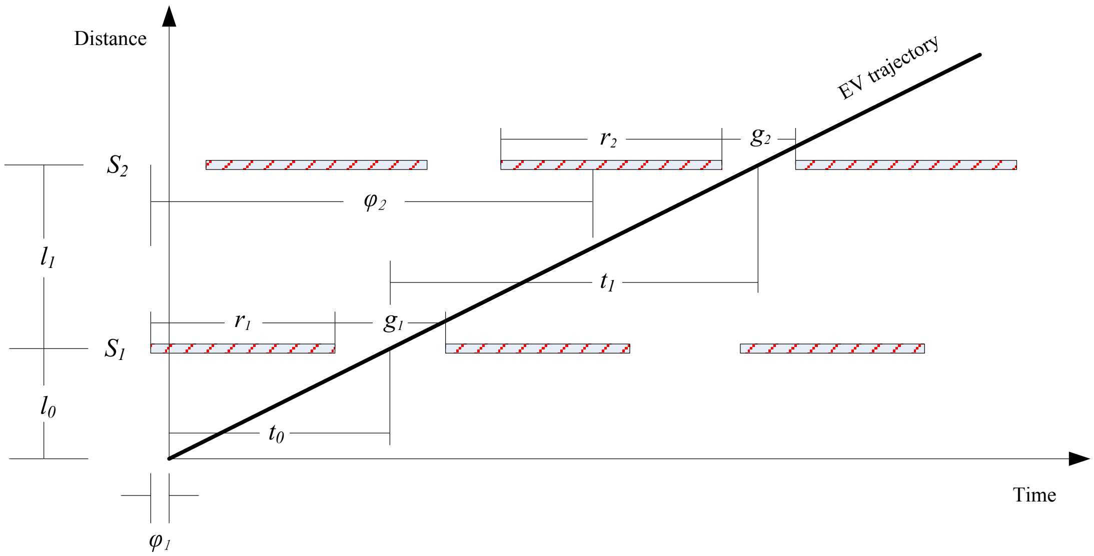

Figure 3. Time-space diagram for the EVSC approach.

Note that value of Δ_i can be either positive or negative. This can be explained clearly in Fig. 2. The figure shows a typical signal setting with 4 phases. Phase 1 and phase 3 are through phases, and phase 2 and phase 4 are left turn phases.

Suppose the green phases for M_{i-1} and M_i are phase 3 and phase 2 respectively. Since phase 2 is priori to phase 3 inner a cycle, this results in

$$\Delta_i=-\left(\frac{1}{2}g_i+\frac{1}{2}g_{i-1}\right)<0. \quad (1)$$

If otherwise green phases for M_{i-1} and M_i (i.e. g_{i-1} and g_i) are exchanged, then

$$\Delta_i=\frac{1}{2}g_i+\frac{1}{2}g_{i-1}>0. \quad (2)$$

In other cases where green phases for M_{i-1} and M_i are the same,

$$\Delta_i=0\,. \quad (3)$$

The above equations for calculating Δ_i are only applicable when $i=2, \cdots, n$. The value of Δ_1 should also be known. Assuming the time when the EV starts its trip is T. Define

$$\hat{g}_0=T \bmod c. \quad (4)$$

Then $\hat{g}_0$ can be treated as the midpoint of green phase at node 0 (although there is no signal at node 0). And the value of Δ_1 can be calculated as the offset between $\hat{g}_0$ and the midpoint of g_1.

After these definitions, the problem is to calculate φ_i such that it is just half the green phase each time EV passes the intersection. It is expected that the optimal cycle length and splits are given before the calculation. Time-space diagram is usually used to help with signal coordination analysis. See Fig. 3. Travel time from node i to node $i+1$ can be calculated as

$$t_i = l_i / v. \quad (5)$$

To make sure that the EV passes the intersection at midpoint of the green phase each time, the following equation must holds:

$$t_i=\varphi_{i+1}+\Delta_{i+1} \quad (6)$$

where $i = 0, \cdots, n$.From this equation we can get the relative offset φ_i for each signal. And the real offset of each signal can be calculated as

$$\Phi_i=\sum_{j=0}^{i}\varphi_j \bmod c \in [0,c) \quad (7)$$

III. Experiments and Results

In this manuscript a small sub road network in Qingdao, China is taken for the simulation experiments (see Fig. 4). The sub network is composed of an east-west main road and a north-south side road connecting the origin and destination of the emergency corridor. The main road has four standard lanes each way within which one is reserved for bus service only. The side road is a typical two-way two-lane highway. There are three main crossings and two minor crossing along the main road, and three minor crossings along the side road. The total length of the corridor is about 2.8 kilometers.

The simulations are conducted using Paramics. Paramics is an excellent commercial software system for microscopic traffic simulation and management. It has great computation performance with 3D display capability of the whole network. Post-simulation analysis is convenient with the provided traffic analysis suite called “Analyser”. It provides a powerful plugin development framework based on C++ for users to implement user-defined control of the simulation. More details about this software can be found in [15]. The plugin development document for signal control can be referred to [16].

Before an EV’s departure, it should first send a priority request to the traffic signal control center with fundamental information including origin, destination, desired speed, and the corridor it will take. After receiving the request, the control center executes the calculation process described in

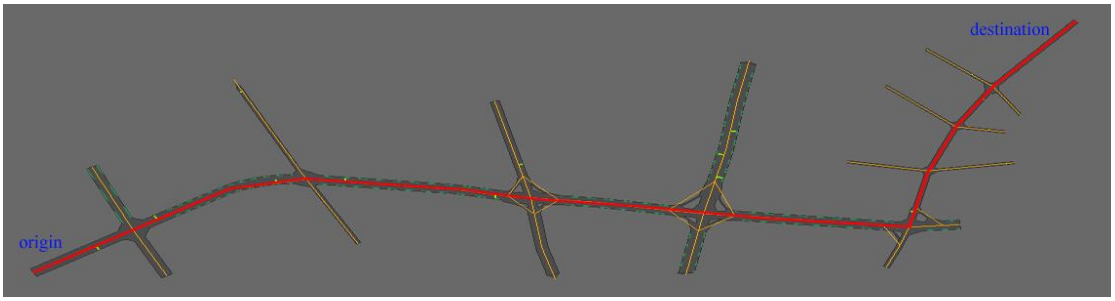

Figure 4. The emergency corridor in Qingdao, China for the case study.

TABLE I. SIMULATION RESULTS WITH DIFFERENT SIGNAL SETTINGS

Traffic Measurements	Normal Setting	SC Setting	Deviation Percent 1	EVSC Setting	Deviation Percent 2
Avg. EV Travel Time (seconds)	593	531	−10.5%	388	−26.9%
Overall Speed (kilometers/hour)	28.9	28.5	−1.4%	30.1	+5.6%
Avg. Delay (seconds/vehicle)	254	235	−7.5%	189	−19.6%
Avg. Stops (stops/vehicle)	0.55	0.65	+18.2%	0.69	+6.2%

TABLE II. AVERAGE NUMBER OF STOPS AT INTERSECTIONS

Avg. Stops (stops/vehicle)	Main Road											Side Road						
	Node 1		*Node 2*		*Node 3*		*Node 4*		*Node 5*		*Sum*	*Node 6*		*Node 7*		*Node 8*		*Sum*
	EB	WB	EB	WB	EB	WB	EB	WB	EB	WB		NB	SB	NB	SB	NB	SB	
Normal Setting		0.55	0.87	1.77	0.51	0.32	0.39	0.64	0.36	0.60	6.00	0.12	0.13	0.20	0.12	0.10	0.32	0.98
SC Setting		0.80	0.98	2.74	0.37	0.25	0.38	0.41	0.34	0.45	6.71	1.16	0.06	0.23	0.14	0.04	0.29	1.91
EVSC Setting		0.64	1.14	3.78	0.32	0.39	0.36	0.45	0.30	0.33	7.71	0.27	0.17	0.21	0.16	0.10	0.21	1.11

EB: Eastbound; WB: Westbound; NB: Northbound; SB: Southbound

section II and adjusts the traffic signal settings along the corridor. A reply should be sent back to the EV telling that the signals have been ready. After arriving at the incident scene, the EV reports its arrival to the control center such that the control center knows it is time to restore the normal signal settings.

We conducted simulations with three different types of traffic signal settings. They are normal setting (i.e. current signal setting in use), signal coordination (SC) setting without designed offsets for EVs, and emergency vehicle signal coordination (EVSC) setting respectively. Under EVSC setting, the green-wave speed, i.e. the expected EV speed, is set to be 40 km/h. Multiple traffic measurements are compared between the two scenes. Except for average EV travel time, other measurements including overall speed from origin to destination, average intersection delay and number of stops are also compared. Each simulation is conducted 10 times with different initial random seeds to obtain the average values. The results are summarized in table I. Traffic measurement changes of SC setting compared with normal setting are presented in column "Deviation Percent 1", and those of EVSC setting compared with SC setting are presented in column "Deviation Percent 2".

From table I we can see that signal coordination operation can improve traffic condition to some degree. With SC setting compared with normal setting, the average EV travel time is reduced by 10.5% and average delay by 7.5%. While the minor negative impact on overall speed can be neglected, the average number of stops is increased by 18.2%.

If we apply the EVSC operation instead, the average EV travel time along the corridor can be further reduced by 143 seconds, corresponding to a substantial improvement of 26.9%. Although this improvement is not exceptional compared with some existing EVSP systems, it is achieved with a much easier way, indicating a good potential for EVSC operation in facilitating EVs' passing along the emergency corridor. Level of service in terms of overall speed and average delay is also improved by 5.6% and 19.6%. This is because vehicles with the same origin and destination as EVs can also benefit from the EVSC setting. Only the number of average stops is increased. But the difference is minor.

To explore the reason why the number of average stops is increased, more data are analyzed. Simulation results in terms of average stops at intersections are presented in table II. From the table we can see that most of the stops are observed on the main road. This is caused because the main road and side road have different flow patterns. The ratio of through volume to left turn volume on the main road is much higher than that on the side road. But all the intersections share the same green phase length for each movement under coordination operation. In this case green phase for through movement is not long enough to clear the queues on the main road. This can be seen clearly in table II. Without signal coordination, each signal is configured separately to accommodate to the single intersection's flow pattern. The average number of stops is acceptable. In the case where signals are coordinated without designed offsets for EVs, the average number of stops on the main road and side road increases by 11.8% and 94.9% respectively. With EVSC setting, the number decreases by 41.9% on the side road. But a further increase of 14.9% is observed on the main road because of heavy through volume.

IV. CONCLUSIONS AND FUTURE WORK

With regard to EV promoting problem, there exist many EVSP systems. Though reported to be effective in reducing EV travel time, EVSP systems share some disadvantages. The most salient problem is they produce too much negative impact on the normal traffic streams, especially during peak hours. In addition, they have to break the existing signal coordination along the emergency corridor at most times. We propose an EVSC approach for EV promoting in this paper. It is easily implementable and cost efficient. This approach provides "green wave" for EVs during their rush to the destination thus saving considerable travel time. Since it needs to make the priority request only one time at the starting of the trip, this approach impacts little on the normal traffic streams compared to traditional EVSP systems. The "green wave" is achieved by signal coordination settings. This makes sure that the existing coordination can be maintained. The only additional work to do is adjusting signal offsets. To avoid a sudden interrupt of the normal traffic streams, the offset adjustment can be finished in an incremental way.

The approach proposed has its limitations. It is only applicable in jurisdictions where centralized traffic signal control is implemented. Besides, there is no mechanism to ensure green light each time an EV arrives at the intersection. The EV may encounter a few red lights if too many interference factors make them fail to follow the green wave. In this case it may report a new priority request to the control center. But the total times an EV can report requests should be restricted.

The proposed approach results in static signal coordination settings during the emergency response. Implementing of traffic adaptive signal coordination is a direction for future work. To improve robustness, this approach can be improved by taking more interference variables into consideration. It would be interesting to consider also the occurrence of unexpected events and the impact of it in the traffic signal coordination. Besides, more powerful and accurate analysis methods also need to be developed to evaluate the impacts on signalized corridor operation.

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