Emergency Vehicle oriented Traffic Priority Control Strategy at Intersection in Congested Urban Area

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Abstract

Efficient and safe traffic control strategy for emergency vehicle can reduce its travel time and avoid secondary accident. Based on the analysis of its requirement and object, we proposed a novel control strategy at intersection according to the status of emergency vehicle, which can be divided into three parts: "approaching", "passing "and "recovering", Furthermore potential safety risk caused by emergency vehicle was also taken into account when making control strategy.From the case study we conclude that with control strategy in this paper delay of emergency vehicle can be sharply decreased by 68.63% with only 19.86% loss of average delay of background traffic.

Keywords: priority control strategy, emergency vehicle, congestion judgement, normal strategy recovery, safety risk

1. Introduction

Emergency vehicles, which are carrying out special task, such as ambulance, firefighting, crusing police, engineering rescue for water, power supply ect., are critical to alleviate life and property loss in our society. However, emergency incidents always happen at random, with liitle probability and uncertainty, but severe results [1]. YANG's research found out that when some natural or social incidents happen, probability of survival for wounded is 80% if they can be rescued in 30 minutes, and this number goes sharply down to 40% and 10% respectively, if the rescue time are 60 minutes and 90 minutes [2]. So it's important to plan a "golden life route" between incidents site and emergency resuce agency, and respone these emergency vehicles in time at intsection along the route, and give them priority in green traffic signals, especially in congested donwtown area [3] to shorten their travel time. However, limited by the fixed point traffic information collection, traffic operational manager can not know the status of emergency vehicles in time, which result in the poor traffic control strategy at intersections, and emergency vehicles are drowned in congest traffic flow, which will waste valued rescue time meaninglessly.

In this paper, we proposed a new traffic control strategy which takes the emergency vehicle status and current traffic situation at intersections into account. The main idea of the control strategy is to predict the arrival time of emergency vehicles, clear the queue at intersection in advance, and recover the normal control strategy as soon as possible to relief the impact of traffic in conflicting roads. Furthermore, potential safety risk caused by emergency vehicle was also considered. Finally, with a case study, the benifit from the control strategy was also analyzed

2. Emergency Control Object Fuction

Emergency traffic control, to some extent, has something to do with bus priority control, so in early study, researchers took two as the same problem called "priority and preemption", and separated them later since 1980, and defined emergency control as preemption, which is highest level.

About its object, most researchers believed that minimal travel time of emergency vehicle should be first, from Kolesar (1975) to Louisell (2005), researchers did large prediction work on it [4, 5].

However, Amalia Vrachnou (2003) 's work [6] showed that at intersection there were lots of potential safety risk caused by emergency vehicle, which may result to severe even fatal accidents. So emergency traffic control not means absolute right of way, it should guarantee against secondary accident.

In recent years, with the increasing congestion in urban area, on the premise of mobility of emergency vehicle, how to alleviate its disturbance and impact on usual social vehicles became the new issue to study [7].

Summarizing issues above, about the travel time of emergency, it can be described as follow:

$$T = T_l + T_i = \frac{L}{V_f} + t_e + \frac{l_0}{v_0} + t_w + t_s \tag{1}$$

Where T is the total trvavel time, T_l is travel time in links, T_i is the time going through the intersections. About t_l, we can get it through follwing formula:

$$T_l = L / v_f + t_e \tag{2}$$

Where v_f is the free speed of emergency vehicle, t_e is its delay time because of vehicles (such as lane change, car following) in links which prevent it from free driving.

About t_i, it includes three parts as follow:

$$T_i = l_0 / v_0 + t_w + t_l \tag{3}$$

Where l_0 / v_0 is the the time emergency vehicle traveling through the intersection, t_w is the waiting delay because of traffic signals at intersection, t_l is the loss time caused by decelration , acceration, queue dispersion in front of intersection. So we can see that t_w, t_l is closely related to traffic control signal.

About the potential safety risk, two factors were taken into account, probability of occurence of accident and its severity. The former factor is mainly related to traffic volume or saturation ratio x if we assume that capacity do not change, JI's research got the relationship [8], see as formula 4. The later factor is mainly related to speed, higher speed meand more severe injuries and deaths if accident happens, FHWA's conclusion [9] was given as formula 5:

$$P = 2371.1x^2 - 3231.5x + 1656.1 \tag{4}$$

Where P is the probability of occurence of accident, x is the saturation ratio which equal to volume divided by capacity.

$$L = (v / 71)^4 \tag{5}$$

Where L is loss of accidents caused by emergency rescue vehicle, v is the speed of vehicles. So we can get the safety risk as follow:

$$R = P\square L = (2371.1x^2 - 3231.5x + 1656.1)(v / 71)^4 \tag{6}$$

Where R is the safety risk.

About the effect of emergency vehicle to soical traffic (we call "background traffic"), delay at interesection was selected as the performance index.

$$d = \frac{c\left(1 - g/c\right)^2}{2\left(1 - q/S\right)} \tag{7}$$

Where d is the average delay of background traffic, g is the green time, c is the cycle, q is the traffic volume, S is the saturated flow. We can see that when the emergency vehicle is approaching, green time of conflicting movement is sharply shorten, so the delay will be longer, it's important to compensate this green loss in next one or several cycles.

Overall, we get the emergency rescue control as a multi-object optimization problem, the object fuction is:

$$\min(T, R, d) \tag{8}$$

Where T and d are funciosn of signal timing parameters such as cycle, green time, R is the function of speed and volume, which we will take into account when determing yellow time.

3. Emergency Oriented Traffic Priority Control

Considering the object above, we dicide to take time series when making control of emergency vehicle. When approaching the intersection, judge the congestion status and disperse the queue to make sure that emergency will pass through the intersection without stop and delay, detailed in chapter 3.1; when passing the intersection, priority control will be taken in chapter 3.1, meanwhile, safety issues will also be studied in chapter 3.4, and after emergency vehicles' passage, recovery strategy will be carried out, detailed in chapter 3.4.

3.1. Congested Intesection Judgement and Dispersion

In congested condition, queue length is the major factor, considering the storage space between intersections, we definite queue ratio as follow:

$$R_q = \frac{Q_0}{Q_c} \tag{9}$$

Where R_q the queue ratio at links, Q_0 is the number of queue vehicles, Q_c is the maxim storage number of vehicle in link. When Q_0 approaching to certain value, the intesection will be blocked or jams, we definite this as Q_j, so congested queue ratio is:

$$R_j = \frac{Q_j}{Q_c} \tag{10}$$

In this way, we can get the congestion judgement criteria as follow:

$$I_c = \frac{R_q}{R_J} = \frac{Q_0/Q_c}{Q_j/Q_c} = \frac{Q_0}{Q_j} \tag{11}$$

Where I_c is the Congestion Index.

If $I_c \geq 1$, the intersection may blocked because of stochastic oversaturation, it's suggested that the emergency vehicles don't selected the rout including this intersection, if unavoidable, it's suggested to interrupt other movements immediately to give the movements of the emergency vehicle more green time to clear the queue in advance.

If $I_{th} \leq I_c \leq 1$ (where I_{th} is the threshold of congestion), the storage space is not enough for queuing, measures should be carried out to restrict the irrelated movement of traffic flow from upstream, and queue clearance should also start.

About the dispersion of congestion intersection, we first definite intersections along route (IR) and background intersections (BI), see Figure1. And then two methods was provided, one is interrupt traffic from BI totally till maximal red time which we call "closure", the other one is giving it the minimal green time which we call "minimal green transition". Two conditions are given as follow to choose themethods above.

(1) Distance from emergency vehicle to congested intersection, see as formula 12. If the "minimal green transition" can not clear the the queue, we have to close totally.

$$l < v_{EV} n C \tag{12}$$

Where l the distance form emergency vehicle to intersection is, v_{EV} is the speed of emergency vehicle, C is the cycle time of the congested intersection, and n is the number of cycle, which is decided by cycle time and traffic volume.

(2) Traffic volume distribution. We definite distribution coefficient D as follow:

$$D_i = \frac{q_i}{\frac{1}{m}\sum_{i=1}^{m} q_i} \tag{13}$$

Where is q_i is the volume of movement *i* at the upstream intersection, *m* is the total number of movements at the upstream intersection. Judge the maximum D_i, if it's the movement of emergency vehicle, the upstream intersection should totoally close other movements except movement of emergency vehicle, or give them minimal green time, depending Congestion Index I_c.
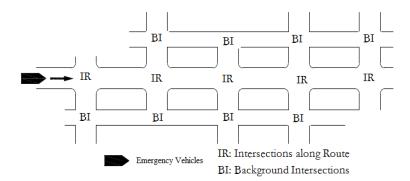

Figure 1. Network and Intersection Definition for Emergency Vehicle Control

3.2 Priority Passage Control

When emergency vehicle approaching the intersection, we judge its the arrival time, and compare it with the signal display status, if the phase of emergency vehicle is not green, we should adjust the signal timging in following ways: (1) green extension, (2) green activation in advance, (3) phase jump.

(1) Green extension

When emergency vehicle arrives at detector at time *t*, we judge the signal status, if satisfy following condition as formula 14, green duration will extend Δg, which is equal to L/V_{EV}, to guarantee the passage of emergency vehicle.

$$g_{EV} - \frac{L}{V_{EV}} < t < g_{EV}$$

$$g_{EV} + \frac{L}{V_{EV}} < g_{max} \tag{14}$$

$$g_{next} - \frac{L}{V_{EV}} \geq g_{next-min}$$

Where t is the arrival time at detector, g_{EV} is the green time duration of phase of emergency vehicle, L is the distance from detector to stop line, V_{EV} is the speed of emergency vehicle, g_{next} is the green time of next phase, $g_{next-min}$ is the minimal green time of next phase, g_{max} is the maximum green time of the phase of emergency vehicle, which is decribed as follow:

$$g_{max} = C - Loss - \sum_i g_{i\ min} \tag{15}$$

Where $Loss$ is the total loss time in one cycle, $g_{i\ min}$ is the minimal green duration of phase i, which include all phases except phase of emergency vehicle.

(2) Green activation in advance

If the arrival time of emergency vehicle arrives is at end of red duration, it's suggested to cut off the the red signal, and transit it to green, which we call"green activation in advance". However, condition should be satisfied as follow:

$$g_{pre-min} - \frac{L}{V_{EV}} < t < g_{pre} - \frac{L}{V_{EV}} \tag{16}$$

Where g_{pre} is the green time of previous phase, $g_{pre-min}$ is the minimal green time of previous phase, others have the same meaning with formula 14. If the arrival time falls into the minmal green of previous phase, the emergency vehicle has to wait till it finish, see as formula 16.

$$t_{pre-st} < t < g_{pre-min} - \frac{L}{V_{EV}} \tag{17}$$

Where t_{pre-st} is the start time of previous phase, others have the same meaning with formula 14 and 16.

(3) Phase insertion and jump

If the arrival time is not far away from the phase of emergency vehicle, the previous pahse, nor at the end of emergency phase see formula 17, two adjustment ways above are out of service, we need jump to the emergency directly, see as Figure 2. We assumpe phase 1 as the current phase when the emergency vehicle arrives, and phase 3 as the phase servicing for the emergency movement (we call "emergency phase").

There are three cases we considered

(a) jump to the emergency phase 3 after phase 1, ingnore phase 2, and recovery next cycle after the emergency passage. In this case phases ignored are victimized, so usually they are not important, such as minor traffic flow.

(b) jump to the emergency phase 3 after phase 1 and recovery to phase 2, another word, change sequence of phase 2 and phase 3. This case can reduce the delay of phases ignored in case a, however, because of insertion of emergency phase, there is still delay increasement for these phases.
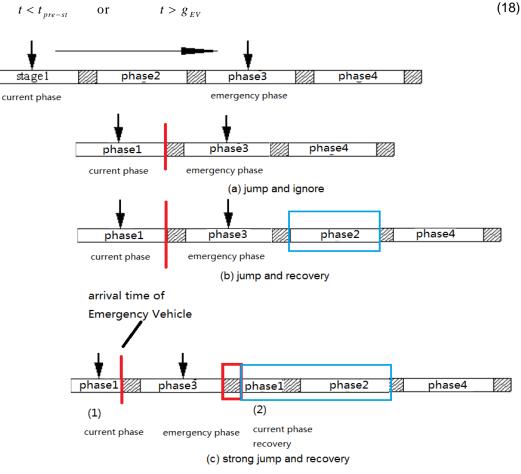
(c) if the end phase 1 is too long for emergency vehicle waiting or the situation is very serious, at its arrival time, jump to phase 3 after green interval (shaded area in figure because of safety consideration), and then after phase 3, go on the rest part of phase 1 and phase2. This case is most efficient for emergency vehicle, but worst for other traffic, and because phase 1 is divided into two parts, so one green interval is added, see red rectangle in Figure 2 (c), the cycle is also extended.

$$t < t_{pre-st} \qquad \text{or} \qquad t > g_{EV} \qquad\qquad (18)$$

Figure 2. Phase Jump Diagram (3 cases)

3.3. Normal Control Strategy Recovery

Because of emergency phase, traffic flow in other phases will be affected. In case of "green extension", all following phases are affected, while in case of "green activation in advance", the previous is affected, and in case of "phase jump", the phases that have been jumped are affected, we all these "affected phase".

After passage of emergency vehicle, compare the summation of queue caused by emergency phase and the arrival traffic volume with its depature traffic volume in "affected phase", if the the former one is greater then the later one, see as formula 19, which means there is residual queue of "affect phase" because of emergency phase, so green duration of this phase should be extend.

$$\lambda_i g_i + L_{init-i} \geq q_i g_i \quad i=1,2,3,...n \qquad\qquad (19)$$

Where i is the number of affected phase, λ_i is the arrival rate in phase i, g_i is the green duration time of phase i, L_{init-i} is the initial queue length at the beginning of phase i, q_i is the departure rate in phase i.

All affected phases which satisfy formula 18 (we call "serious affected phases") should be extended to certain value as formula 19 theoretically, however because of the limitation of maximum green time of phases and avoidance of re-affectiveness to other phases, we should recover to normal signal timing increasingly in several cycles, not sharply, because sharp recovery may lead to large fluctuation of traffic flow.

$$g_{j-exth} = L_{init-j} / (q_j - \lambda_j) - g_j \tag{20}$$

Where j is the number of serious affected phases, g_{j-exth} is the green extension time of phase j theoretically.

In the next cycle, certain percentage green time of emergency phase should be given to other phases, the allocation proportion should be decided as follow:

$$\alpha_j = \frac{g_{j-exth}}{\sum_i g_{j-exth}} \tag{21}$$

Where α_j is the allocation proportion of affected phase j.

However, green time of emergency phase can not shortened too much to affect its operation in next cycle, which can be expressed as follow:

$$(1 - \beta) g_{EV} (q_{EV} - \lambda_{EV}) > 0 \tag{22}$$

Where β is the percentage of shortened green time of emergency phase, g_{EV} is its normal green time in next cycle, and q_{EV}, λ_{EV} are departure and arrival ratio in next cycle respectively.

So we can get that the shortend percentage:

$$\beta < 1 - \frac{(q_{EV} - \lambda_{EV})}{g_{EV}} \tag{23}$$

However, if β is smaller than 10%, and 10% is adopted to compensate affected phases because of priority passage control of emergency vehicle.

Finally, we can get the green extension time of serious affected phases in next cycle as formula 24:

$$g_{j-extension} = \alpha_j \beta \square g_{EV} \tag{24}$$

If one cycle can not recover to the normal signal timing, repeat the procedure from formula 21 to 24 till the affectiveness of emergency phase disappear. One thing that should be mentioned when doing the repeat work is that we will replace g_{j-exth} with $g_{j-exth} - g_{j-extension}$ in formula 21.

3.4. Potential Safety Risky Consideration
As chapter 2 mentioned, consequence of traffic accident caused by emergency vehicle is usually serious, so it's necessary to take safety issues into accout when making control strategy, especially phase transition between emergency phase and others.

When approaching the the intersection with high speed at the beginning of yellow time, driver has risky to trap in an area for confused decision. On one side, with high speed he can't stop safely (usually when the vehicle stop totally, it has already passed the stop line at intersection, it's dangerous to collide with other vehicle (see "Cannot stop" area in Figure 3); on the other side, the distance is so far that he has to stop, or he will pass the stop line at red

signal (See "Cannot pass" area), when trapping the overlap area (we call "Dilemma zone",see "DZ" in Figure 3), drive don't know what he will do next.
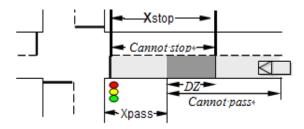

Figure 3. Dilemma Zone

We definite that at the beginning of the yellow signal, distance the emergency vehicle from stop line is x (m) and speed is v_0 (m/s) .If the diver decides to pass the intersection, we assume he will go with the constant speed v_0 in the yellow duration T_y, if he decides to stop, we assume that deceleration rate is a constant value a_, and the reaction time for the driver to stop is δ_- .

The minimum distance for a vehicle to stop before stop bar, can be expressed as follows:

$$x_{Stop} \geq \frac{v_0^2}{2a_-} + v_0\delta_- \qquad (25)$$

If the driver decide to pass the stop line before signal turning red, we can define the maximum distance x_{Pass} (m) as:

$$x_{Pass} \leq v_0 T_Y \qquad (26)$$

The range of dilemma zone can be given by inequality 27:

$$v_0 T_Y \leq x < \frac{v_0^2}{2a_-} + v_0\delta_- \qquad (27)$$

From formula 27, we can see that if $x_{Pass} \geq x_{stop}$, the dilemma zone will disapper. In this case, we can get following forluma:

$$T_Y \geq \frac{v_0}{2a_-} + \delta_- \qquad (28)$$

So we can adjust the yellow duration of traffic signal in phase transition depending on speed, deceleration rate and reaction time of driver.

4. Case Study

In this chapter, we select intersection at Jinqiao Road and Zhangyang Road as the study point, which are two crossing arterials at Pudong District, Shanghai, China. Figure 4 gives its lane and phase configuration.

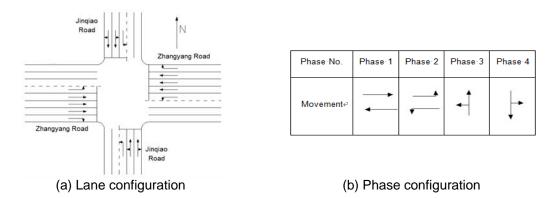(a) Lane configuration   (b) Phase configuration

Figure 4. Configuration Information of Study Intersection

In this study, we assume that phase 4 is the emergency phase. Moreover, we load different traffic volume (saturation ratio from 0.6 to 1) to simulate different congested different scenarios, and corrosponding control strategies are gengerated by classical signal timing optimization software Syncro, based on which we adjust signal timing to satisfy the requirement of object of emergency vehicle in chapter 2. Finally, we simulate all these scenairos, with and without emergency-oriented priority control in mircosoft traffic simulation software VISSIM, and get results in Table 1 and Table 2.

We can see that with the control strategy in this study, the average delay of emergency vehicle sharply deacreased by 68.63%, while average delay of background vehicles increased only 19.86%. Furthermore, in diffenent scenarios, the performance improvements are also different, see as Figure 5, with the increasing of saturation ratio of intersection, the benefit from the control strategy in this study seems going receding.

About the safety consideration and strategy recovery, we can see that at lower saturation ratio, the effect seems great, but when it's near 1, maybe because of low speed, no vehicle in simulation trapped in delimma zone. Moreover, with the increasement of saturation ratio, the number of cycle for recovery is also increasing sharply.
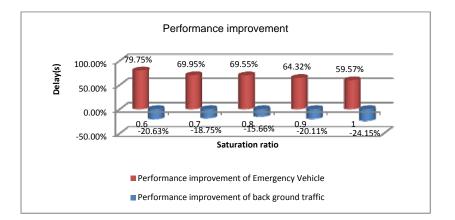

Figure 5. Perfomence Improvement of Control Strategy in this Study

5. Conlusion

In this paper, based on the study of control object of emergency vehicle, we proposed a new signal control strategy for emergency vehicle at intersection, which can be divided into three parts depending on time series: "approaching", "passing "and "recovering". Furthermore, from the simulation and validation work, we can conclude that, with the strategy in this paper, delay of emergency vehicle can be sharply decreased with relative few delay loss of background traffic. However, with the increasing of saturation ratio of intersection, the benefit

seems going receding. So it's suggested that when choosing route for emergency vehicle, we'd better to avoid intersection whose saturation ratio is near 1.0 as much as possible. Furthermore, the strategy in this paper is only for the isolated intersection, maybe the coordinated control strategy in arterial or route of emergency vehicle will give more benefit for the reduction of travel time of emergency vehicle, which is also the work we will go on in the future.

Table 1. Vehicle Delays at Study Intersection

	Delay of emergency vehicles (s)					Average delay of background vehicles				
	Saturation ratio at intersection					Saturation ratio at intersection				
	0.6	0.7	0.8	0.9	1	0.6	0.7	0.8	0.9	1
Control strategy of Synchro	15.8	20.3	31.2	38.4	46.5	16.0	20.8	33.2	37.8	47.2
Control strategy in this study	3.2	6.1	9.5	13.7	18.8	19.3	24.7	38.4	45.4	58.6
Performance improvement	79.75%	69.95%	69.55%	64.32%	59.57%	-20.63%	-18.75%	-15.66%	-20.11%	-24.15%
Average Performance improvement	68.63%					-19.86%				

Table 2. Simulation Results About Safety Consideration and Strategy Recovery

	Number of vehicles trapped in dilemma zone					Number of cycle for recovery				
	Saturation ratio at intersection					Saturation ratio at intersection				
	0.6	0.7	0.8	0.9	1	0.6	0.7	0.8	0.9	1
Control strategy of Synchro	8	5	1	0	0	—	—	—	—	—
Control strategy in this study	6	4	1	0	0	1	2	2	4	6
Performance improvement	25.00%	20.00%	0.00%	0.00%	0.00%	—	—	—	—	—

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