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A MODEL FOR ACCELERATING DISCHARGE OF LANE TRAFFIC TO FACILITATE INTERSECTION ACCESS BY EVs

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ABSTRACT

Intelligent Transportation System (ITS) is the synergy of information technology, real-time control, and communication networks. The system is expected to perform more complex traffic arrangements, in particular, traffic management of Emergency Vehicles (EV) such as fire trucks, ambulances, and so forth. Implementation of traffic management using only Traffic Signal Pre-emption does not give enough space for an EV to cross an intersection safely, especially on streets where there is only one lane. This paper proposes a model of accelerated emptying of traffic in front of EVs. Accelerated emptying model uses historical approach, based on current characteristics of traffic. For example, if the normal vehicle speed is equal to the EV speed before accelerated emptying, the system indicator will be 0%, thereby indicating no need for accelerated emptying. Similarly, a negative system indicator result means an accelerated emptying process is not necessary. However, if the system indicator is close to 100%, this result indicates accelerated emptying is necessary.

Keywords: Acceleration discharge; Emergency vehicle; Historical data; Model

1. INTRODUCTION

Researchers around the world have concerned themselves with how to efficiently exploit capacity of the existing transportation infrastructure (Sumaryo et al., 2014). Intelligent Transportation System (ITS) was proposed to solve traffic problems; it consists of information technology, real-time control, and network communications. ITS researchers have received considerable attention worldwide, including: Kim and Mahmassani (2015); Lim (2016); Lopez-Garcia et al. (2016); Loorbach and Shiroyama (2016); Mannion et al. (2016); Hassn et al. (2016).

The transportation system is a complex and dynamic system that is difficult to model with precision (Li et al., 2007). However, without proper modeling, characteristics of the transportation system cannot be properly identified for the purpose of evaluating existing methods and identifying potential problems.

Traffic flow modeling, using queuing theory, has been performed by numerous experts (Yang & Yang, 2014; Fuyu et al., 2014; Sumaryo et al., 2015).

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One traffic problem identified in traffic flow modeling is the management of Emergency EV such as fire trucks and ambulances (Sumaryo et al., 2014). Signal control for handling EV requires a pre-emptive control, designed and operated to give the most important classes of vehicles the right-of-way through a signal or intersection (Kittelson & Associates, Inc., 2008). Many researchers have examined the appropriate method for pre-emptive control (Huang et al., 2011; He et al., 2011; Shruthi & Vinodha, 2012; Goel et al., 2012; Kuang & Xu, 2012; Chakraborty et al., 2014). Research shows that some benefits associated with traffic signal pre-emption include: improved response time/travel times for EV; improved safety; and, reliability for vehicles receiving pre-emptive right-of-way (Kittelson & Associates, Inc., 2008).

There are several technologies available for the detection of vehicles that invoke pre-emptive arrangements, including: lights, siren sounds, pavement loops, and radio transmissions (Kittelson & Associates, Inc., 2008). These technologies are activated when the vehicle is approaching the intersection. Figure 1 (below) shows an example of how the pre-emptive process is activated. First, the vehicle sends a priority signal to the detector or sensor as the EV approaches the intersection. The detector then sends a signal to the processing unit. Next, the processing unit sends an activation request for the pre-emptive sequence (i.e. extended green signal or red truncation signal) to the traffic system controller. Finally, the controller sends a request to the traffic signal. At present, considerable research exists on the implementation of pre-emptive arrangements (Wang et al., 2013; Hashim et al., 2013; EShanthini & Sreeja, 2016).

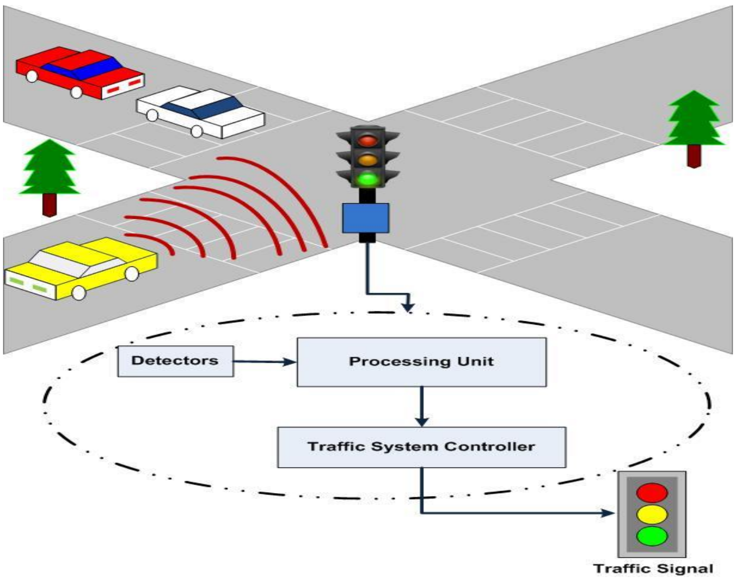

Figure 1 The example of pre-emptive detection of EV

However, implementation using only traffic signal pre-emption is not enough to give adequate space for an EV to cross an intersection safely. Therefore, additional processes are necessary, such as accelerating the discharge of vehicles in front of the EV. Discharging congestion in front of EVs is crucial, especially if the road has only one lane.

Most experts have only briefly considered emptying vehicle congestion in front of EVs (Huang et al., 2011; Kamalanathsharma, 2010; Wang et al., 2013). Until now, studies have not examined means of promptly reducing lane traffic congestion in front of EVs. In 2011, the procedure proposed by Huang, Yang and Ma identified a need for accelerated discharging at a vulnerable position of congestion. However, the research did not develop a process for emptying. In 2010, Kamalanathsharma's research only identified the time required by the last vehicle in the queue to reach the intersection. While this did provide a basis for determining the pre-emptive offset, again the research lacked further development of an emptying process. Likewise, the research conducted by Wang et al. (2013) predicted the time required for emptying the queue based on queue history, but their approach did not guarantee the avoidance of collision to a normal vehicle in front of the EV by the EV.

This research was aimed to develop a method and model for accelerated discharging of traffic in front of an EV at a single intersection. Accelerated discharging is the process of emptying a queue of normal vehicles immediately in front of the EV at the arm of the intersection. The method developed by Wang et al. (2013), is a pre-emptive extension system called TONGJI-Signal Emergency Vehicle Pre-emption System (TJ-EVSP) that can be applied to other pre-emptive systems. The proposed method and model of accelerated emptying presented here follows an historical approach. The tail of the queue path does not intersect with the trajectory of the EV across the intersection. The simulation test of the accelerated emptying model was conducted using MATLAB.

2. METHODS

2.1. Accelerated Traffic Discharging Method Based on the Historical Approach

An historical approach is based on existing characteristics of traffic. The historical characteristics of traffic adopted in this research were taken from the results proposed by Wang et al. (2013). VQ is defined as the speed tail of the queue with the distance from the stop line LQ. Logarithmic regression approach was then performed to obtain the relationship between VQ and LQ.

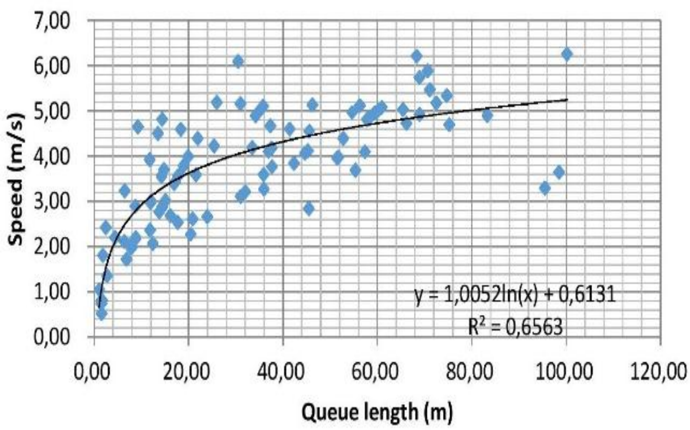

Figure 2 The relationship between VQ and LQ (Wang et al., 2013)

From the data obtained using the regression approach or logarithmic trend line (see Figure 2), the following functional equation was found:

$$VQ = 1.0052\ln(LQ) + 0.6131 \quad (1)$$

Based on the pre-emption phase algorithms studied by Wang et al. (2013), the emptying traffic time for the normal vehicle when the signal is red and there is no collision with an EV is given by:

$$\Delta t > 0 \text{ or } TE - TQ - t\varepsilon > 0 \text{ or } TE > TQ + t\varepsilon \quad (2)$$

Δt is the extra time before pre-emption command was executed. TE is the planned travel time of an EV. TQ is the estimated clearance time of normal vehicles (stopped or in a continuous flow) in front of EV. The $t\varepsilon$ indicates a transitional time period, which consists of traffic signal switch time and headway in a free-flow condition.

The operational relationship is the slope of the trajectory tail (Q_{tail}), which is at least equal to or greater than the slope of the trajectory EV, expressed as:

$$VQ^* \geq VE \tag{3}$$

In other words, the speed of Q_{tail} (previously VQ) must be accelerated so that the speed becomes VQ^*. VQ^* is the speed of the tail of the normal vehicle queue in front of an EV, after being subjected to the accelerated emptying process. VE is the speed of EV that is planned. To avoid a collision, the speed of Q_{tail} is changed minimally by VE/VQ times the original VQ speed. The maximum value of VQ^* is primarily determined by: the density of road traffic conditions; road types; and, the level of service expected (Ministry of Transportation, 2006).

Figure 3 describes algorithms for the accelerated discharging process using an historical approach.

Input: *Historical data: LQ (queue tail length) and VQ (queue tail speed)*
Output: *Normal vehicle speed VQ**

1. *Create the approach equation of the relationship between VQ and LQ with appropriate regression.*
2. *Check current: LQ, VE*
3. *Calculate VQ with equation created in 1st step*
4. ***if*** *VQ ≥ VE* ***then***
5. *VQ* = VQ*
6. ***else***
7. *Accelerate the speed of normal vehicle at least (VE/VQ) times the original speed.*
8. *The new speed of normal vehicle is VQ**
9. ***end***

Figure 3 Algorithm for the accelerated discharging process using an historical approach

The algorithm above assumes an installation of equipment that supports a real-time calculation for LQ and VE/VQ, and immediately notifies the driver. The acceleration algorithm in Figure 3 is based on an existing pre-emptive algorithm. In the above algorithm, the speed V_Q can be regarded as a normal vehicle speed at the position of the stop line LQ. As outlined above, the speed of VQ is obtained by the current vehicle position LQ. Based on the equation approach in Figure 3, the magnitude approach of VQ can be obtained based on the relationship between VQ and LQ with appropriate regression.

The calculation assumed all normal vehicles accelerated simultaneously when an EV was detected. In Figure 3, the algorithm output steps 1 and 2 had to first be created and stored in a database in a signal controller. Output steps 3 to 9 were performed in real time. Using this approach, accuracy for determining the magnitude of the acceleration of the normal vehicle speed was governed by output steps 1 and 2.

The following equation describes the accelerated discharging method using the historical approach:

$$KinH = \left[\frac{VE-VQ}{VE}\right] * 100\% \tag{4}$$

where VE is the speed of EV that is planned, and VQ is the normal vehicle speed in front of EV before acceleration.

If the normal vehicle speed before the accelerated emptying process (VQ) is equal to VE, the system indicator will be 0% (KinH value = 0%). This condition indicates there is no requirement for accelerated emptying. If KinH is negative, it also means accelerated emptying is not necessary. However, if the value of the velocity VQ is significantly lower than VE, then the system indicator will be closer to 100%, thereby indicating necessity for accelerated emptying.

2.2. Evaluation of the Accelerated Discharging Effect on Lane Traffic in front of EVs and Travel Time of EVs at a Single Intersection

This evaluation was conducted using the MATLAB program and the simulation was carried out using the queuing theory approach. The system indicator of the accelerated discharging system was based on the average travel time of an EV until reaching an intersection. The system indicator for accelerated discharging can be described by the following equation (Sumaryo, 2016):

$$KA = \left[\frac{TE^{*} - TE}{TE}\right] * 100\% \tag{5}$$

where TE is the planned traveling time of EV, and TE^{*} is the observed travel time or experimental results. A small KA value indicates better performance in the discharging process.

The single intersection model, shown in Figure 4, was modeled to show the movement of traffic from west to east in a single lane.

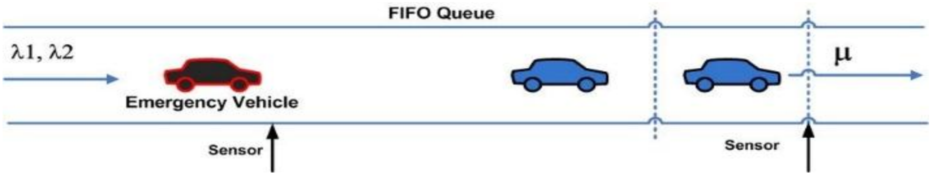

Figure 4 The queue model of the road traffic flows from west to east in the presence of an EV and applies accelerated discharging (Sumaryo, 2016)

The model described in Figure 4 represents the west to east flow of vehicles and an EV before crossing the traffic junction. Priority to all vehicles for road access is considered equal, even for EVs that have a faster than average speed compared to other vehicles. That is because EVs cannot preempt other vehicles in front of it. In the simulations, it was assumed that the vehicles driving from west to east can pass through the intersection without stopping.

In this model, the EV had an average arrival rate λ_1, while normal traffic is historically assumed to have an average arrival rate λ_2. A single server serves a vehicle one piece at a time, with no interruption in accordance to First-In-First-Out (FIFO) discipline with an average service rate μ. Furthermore, it was assumed that the sensors were placed upstream and downstream on the road on the line of the road section. An upstream sensor detects the arrival of an EV on the road, while a downstream sensor detects that an EV has passed the intersection. Travel time of the EV was the difference between when the EV was detected by the upstream sensor until when the EV was detected by the downstream sensor.

The simulation used queuing model M/M/1 if it did not detect the EV on the road. The average service rate was accelerated two to three times the rate of the previous average service if the EV was detected on the road.

Assume LE equals 600 m. That is, the EV distance to an intersection when a pre-emptive request is received). The EV speed (referred to as VE) is assumed to be 40 km/h (Sumaryo, 2016). With these assumptions, the simulation obtained a TE equal to 54 seconds. For example, if the speed V_E is 40 km/h, then the average arrival rate of EV is equal to λ_1 = E×SN = 1 vehicle/km × 40 km/h = 40 vehicles/hour = 0.011 vehicles/sec (Sumaryo, 2016). The average of inter-arrival time of EV is $1/\lambda_1$= 1/(E×SN) = 90.91 seconds. VE is assumed here to be equal to SN (nominal speed). E is the density of the traffic.

The interarrival time distribution is an exponential distribution. For normal vehicles in front of an EV (using historical data), a sample of the average arrival rate (the exponential distribution) is λ_2 = 45 vehicles/minute = 0.75 vehicles/sec or $1/\lambda_2$ = 1.33 seconds. The simulation used the average service rate of μ = 55 vehicles/minute = 0.92 vehicles/sec or average service time 1/μ = 1.087 seconds. Acceleration discharging μ' was assumed to be 2μ.

In the simulation, a SIMULINK program and SimEvent toolbox in MATLAB were used. Traffic generation was divided into two parts, namely EV traffic and normal vehicle traffic. Both sources of traffic were combined in the West Arrival Road block representing a road. Details of the computer simulation models, including verification of the model, is described in Sumaryo (2016).

3. RESULTS AND DISCUSSION

3.1. Relation of the Queue Tail Trajectory with Discharging Acceleration

Examples are outlined in the following section with the data from Wang et al. (2013). The EV speed was 40 km/h = 11.11 m/s. The normal vehicle in front of EV at position 100 m from the stop line had a speed of 1.0052 ln (100) + 0.6131 = 5.24 m/s. Thus, the normal vehicle needed to change its speed to a minimum of VQ^*= 11.11 m/s or 2.12 times the original speed. From that condition, Equation 1 becomes: $2.131\ln(\mathrm{LQ}) + 1.2998$ with LQ = 100 m.

If the normal vehicle in front of EV, at position 10 m from the stop line, has the speed of $1.0052\ln(10) + 0.6131 = 2.928$ 1 m/s, the normal vehicle needs to change its speed to a minimum of VQ^*=11.11 m/s or 3.79 times the original speed. From that condition, Equation 1 becomes: $3.8097\ln(\mathrm{LQ}) + 2.34$ with LQ = 10 m.

If the VQ speed of the Wang data (Wang et al., 2013) is accelerated two times , it is said to be an accelerated emptying of the normal vehicle queue in front of the EV. The relationship between VQ with LQ in Equation 1 can be transformed into the following equation:

$$\mathrm{VQ} = 2.0104\ln(\mathrm{LQ}) + 1.2262 \tag{6}$$

If the VQ speed of the Wang data (Wang et al., 2013) is accelerated three times, it is said to be an accelerated emptying of the normal vehicle queue in front of the EV. The relationship between VQ with LQ in Equation 1 can be expressed as:

$$\mathrm{VQ} = 3.0156\ln(\mathrm{LQ}) + 1.8394 \tag{7}$$

A comparison graph of Equation 1 (denoted as Q_1), Equation 6 (denoted as Q_2) and Equation 7 (detenod as Q_3) are shown in Figures 5 and 6.

Figure 5 shows the LQ- VQ curve with accelerated emptying (Equation 6 and Equation 7), on the condition that the value of LQ is the same as the value of VQ. Assuming that the condition is satisfied, this would give a larger value of VQ than the VQ value from Wang's data (Wang et al., 2013). Since the form of Equation 6 and Equation 7 are equal to Equation 1, the shape of the curves are also similar. However, Figure 5 does not illustrate adequacy of accelerated emptying performed by normal vehicles (i.e. avoidance of collisions or slowing the speed of the EV). Because of that, a TQ- LQ curve, as a trajectory curve, was needed, as shown in Figure 6.

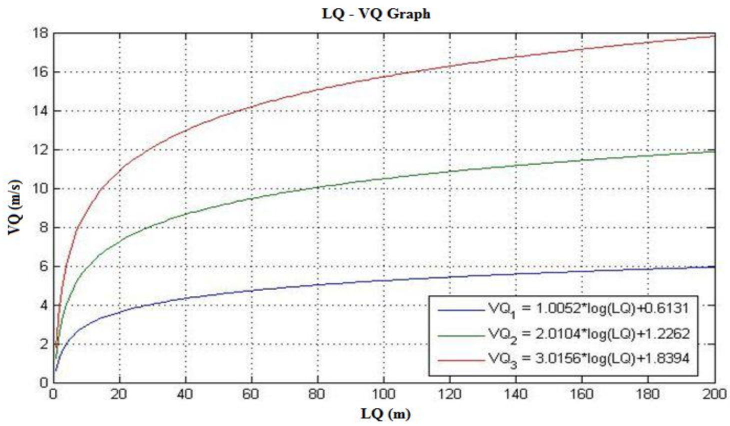

Figure 5 Relationship between LQ – VQ with the acceleration of two and three times the VQ speed as the Wang data (Wang et al., 2013)

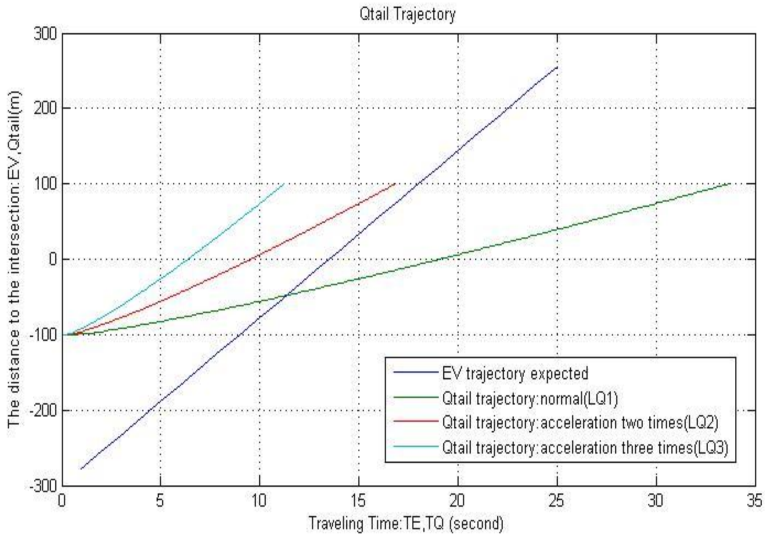

Figure 6 The queue tail trajectory of Wang data (Wang et al., 2013) with and without acceleration using a logarithmic regression with VE =22.22 m/s

Figure 6 shows the accelerated emptying of the queue of vehicles in front of EV (curve LQ2 and LQ3). The accelerated emptying is marked by shifting the cut-off point of the EV trajectory with the path of the normal vehicle in front of an EV. The LQ3 curve shows a trajectory Q_{tail} that does not intersect with the trajectory of EV, so the EV speed (with assumption VE = 22.22 m/s) is not reduced.

The characteristics of the LQ3 curve shows that the accelerated emptying formula, used in combination with the historical data approach, is already validated. The validation method is called Operational Graphics (Law & Kelton, 2000), in which the behaviors of the performance indicators are carried out by the visual display.

3.2. Relation of the Accelerated Discharging Effect of Traffic in front of the EV with Travel Time of EV at a Single Intersection

The results of the simulations are shown in Table 1. Replication is carried out with a 90% confidence or α = 0.1. Using the t distribution table (Law & Kelton, 2000), it is obtained that $t_{M-1,1-\alpha/2}$ = 2.132. The table displays the average travel time for an EV as the result of an experiment using the accelerated discharging model and the TONGJI EV Signal Pre-emption

System (TJ-EVSP) model (Wang et al., 2013). The TJ-EVSP system does not contain an accelerated discharging process.

Table 1 shows the travel time for an EV with an accelerated discharging system that has a travel time much shorter than that of the TJ-EVSP system. This is a logical result because, with accelerated discharging, dense traffic conditions in front of an EV will be reduced much faster than without accelerated discharging. Consequently, the EV speed does not decrease further, as compared to the expected travel time (TE = 54 sec).

Table 1 The comparison of EV travel time by accelerating discharge and TJ-EVSP system

Model	Experimental results of the EV average travel time: TE^*
With the acceleration of discharging 2μ, TE: 54 seconds, VE: 40 km/hour	54.7225 ± 0.3236 seconds
TJ-EVSP, TE: 54 seconds, VE: 40 km/hour	210.4188 ± 34.7845 seconds

Using Table 1, the system indicators for accelerating discharge of traffic can be calculated. With TE equal to 54 seconds and considering the confidence interval, KA had values ranging from 0.74 % to 1.94%. This means that the EV travel time is delayed between 0.74 % to 1.94 % from the planned time TE. This proves that the delay of an EV is reduced if there is an accelerated discharging process.

Table 1 can also be used to compute the amount of improvement fo EV travel time. To illustrate, where TE equals 54 seconds, the simulation result of TE * (Table 1) was 54.3989 seconds to 55.0461 seconds. Alternatively, TJ-EVSP system simulation results had travel time values ranging from 175.6343 sec to 245.2033 sec. Comparing the data, the results show that EV travel time could be improved by (175.6343/54.3989) = 3.229 times to (245.2033/ 55.0461) = 4.4545 times using an accelerated discharging process.

4. CONCLUSION

This paper proposed an accelerated emptying of lane traffic to facilitate access for EVs using an historical approach method that applied past characteristics of traffic. Using the proposed model, the emptying process can be analyzed using the defined system indicator. The results showed that, where the normal vehicle speed before accelerated emptying was the same as the EV speed, the system indicator was at zero percent, thereby indicating no requirement for accelerated emptying. The same results arose for the negative indicator. However, where the system indicator was close to one hundred percent, requirement for the accelerated emptying process was necessary.

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