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IMPROVING INTERSECTION THROUGHPUT USING CONNECTED VEHICLES

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ABSTRACT

This paper proposes a connected vehicle based approach to improve the throughput at signalized intersections and ultimately increase the mobility of a transportation system. Connected vehicle technology demonstrates tremendous potential for improving safety and mobility, as it enables the real-time sharing of vehicle data, including position, speed, acceleration, etc., not only among vehicles but also between vehicles and infrastructure. The proposed approach takes advantage of such real-time data to develop a strategy that maximizes throughput of an isolated intersection locally. Accordingly, the problem is formulated as a two-step centralized optimization. There are two main processes in this method: optimization for vehicles in motion, and optimization for stopped vehicles. The first step maximizes the intersection throughput of vehicles in motion using advisory acceleration. The second one minimizes the total delay of the stopped vehicles by adjusting the positions at which vehicles stop. A case study is also presented to show the efficiency of the proposed approach, which improves the traffic flow throughput of an isolated signalized intersection and reduces the total delay of all vehicles.

Keywords: intersection throughput, traffic operation, connected vehicles

1. INTRODUCTION

Maximizing the throughput of intersections is critical for urban road systems in terms of traffic operations, safety and environmental influences. Increasing the intersection throughput, and in turn the capacity, can help achieve benefits such as reduced congestion and fuel consumption (Milanés et al., 2014). Traditionally, in the highway capacity manual (Transportation Research Board, 2010), an intersection's capacity is defined as a fraction of the connected lanes' vehicle flows (Lioris et al., 2015).

The connected vehicle (CV) is an emerging technology in the area of intelligent transportation systems (ITS) that uses wireless communication between vehicles, infrastructure, and pedestrians based on dedicated short-range communications (DSRC) to enhance existing transportation systems. For instance, researchers have demonstrated how CV technology can significantly enhance traffic safety (Park et al., 2015; Goodall et al., 2013; Sengupta et al., 2007; Stephens et al., 2014). Another interesting application of CV technology is to improve traffic capacity and reduce potential of congestion within transportation systems (Milanés et al., 2014). Two typical types of wireless communication used in CV are vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) communication. These types of communication enable the sharing of real-time data from traffic systems, including position, speed, acceleration, signal phases and timing (SPaT), etc. Via using these real-time data, various methods are proposed to significantly reduce oscillations caused by preceding vehicles and improve the traffic efficiency.

In previous studies, some experimental results have shown that V2V communication can improve the vehicle-following performance between two consecutive vehicles (Milanés et al., 2014; Ploeg et al., 2011; Rajamani and Shladover, 2001; Robinson et al., 2010). Moreover, some studies investigate the string stability of cooperative adaptive cruise control (CACC) systems using V2V communication (Dunbar and Caveney, 2012; Xiao and Gao, 2011). The goal is to deduce the propagated disturbances from the leading vehicles of a platoon in a CACC system. These approaches are using CACC to increase a highway's capacity other than to increase an intersection's capacity (Lioris et al., 2015). In addition to the vehicle-following performance, other researchers have studied departure sequence optimization of multi-traffic streams in an intersection for improving the efficiency of intersections via V2V communication (Guler et al., 2014; Yang et al., 2015) World Conference on Transport Research . Increasing the efficiency of intersections of multi-traffic streams will not increase the throughput of the intersection which is limited by intersection capacity.

Another important type in CV is V2I communication. The types of real-time information that CV-enabled vehicles can obtain from traffic infrastructures include signal phases and timing information from roadside signal controllers and travel times from traffic management centres. V2I connectivity has the potential to improve the acceleration process of vehicles by using traffic light data (Kasać et al., 2011; Park et al., 2015; Szwabowski et al., 2010). Acceleration performance optimization can be achieved when a vehicle is in continuous communication with the traffic light. Via this communication link, the stopped vehicle obtains a prior acceleration rate, which helps improve traffic flow (Park et al., 2015). In addition to the optimization for stopped vehicles, some researchers have focused on green light optimal speed advisory strategies for vehicles in motion using the real-time signal phase and timing data when vehicles are in motion~~.~~ (Katsaros et al., 2011; Rakha and Kamalanathsharma, 2011; Seredynski et al., 2013). By combining the signal phase and timing information with real-time vehicle position data, the optimal speed for each vehicle can be determined and suggested to the driver to improve the traffic throughput and reduce the traffic stop time.

However, the potential of using CV technology to improve intersection throughput can be further exploited for both stopped and moving vehicles, which is not considered in previous studies. In this paper, a two-step optimization algorithm is proposed to improve intersection throughput. To achieve the objective, the proposed algorithm exploits real-time signal phase and timing data received from roadside signal controllers via V2I communication, and combines it with built-in GPS data obtained locally from probe vehicles. The main contributions of this work are listed as follows. First, the proposed method uses CV positioning, which is commonly available in CVs with built-in GPS devices. Also, the signal phase and timing information is also captured and transmitted to the target vehicle via V2I communication. Compared to previous research (Guler et al., 2014; Park et al., 2015) that uses positions and signal phases and timings, the proposed method features multi-data sources and can be used to update the trajectories of both stopped and moving vehicles. With this method, throughput can be improved to a greater extent than in previous studies, using these two types of real-time data: position and SPaT data. In addition, many DSRC products have be released recently, and it is ready to be implemented with the development of CVs. Second, a two-step optimization algorithm is proposed to improve the performance of intersection throughput. Compared to previous studies (Dunbar and Caveney, 2012; Guler et al., 2014), the throughput is improved by optimizing both the ending and beginning of departure vehicle sequence in this method. From our results, it can be seen that for different average vehicle speeds, the traffic throughput of an intersection will increase if the last vehicle in the sequence in motion can accelerate to an appropriate speed. Also, by relocating positions of stopped vehicles via calculating the optimal space headway, total delays are reduced, which means optimizing the beginning of the departure sequence can further improve the throughput. This indicates that the proposed method can simultaneously improve traffic flow throughput for both moving vehicles and stopped vehicles

The rest of the paper is organized as follows. Section 2 gives the problem definition and introduces the proposed idea. Section 3 presents a CV-based throughput optimization algorithm. Section 4 describes the experiment setup for evaluating the proposed method and the numerical results that demonstrate the effectiveness of the proposed method. The last section gives the conclusion of the paper.

2. PROBLEM DEFINITION

An algorithm is proposed to improve the throughput of an isolated intersection, taking into account all individual vehicles approaching the isolated intersection from west bound. A typical signalized intersection consisting of two streets and no turning is considered as the scenario and shown in Figure 1. The objective of this algorithm is to develop a method to maximize the number of approaching vehicles from west bound during the green phase and minimize the total delay of these vehicles.

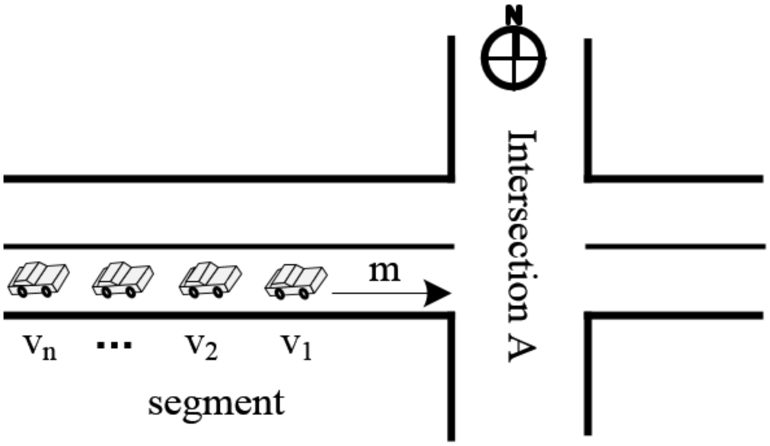


Figure 1: Typical Scenario

As shown in Figure 1, there are *n* vehicles approaching Intersection *A* in a segment when a current signal is switched from a green phase to the next red phase. A general signal timing cycle with only two phases is considered so there are no permitted or protected left-turn phases. There have some lost time for vehicles to start from zero speeds when phases switch from green phases to red phases. The problem is to minimize these lost time of both vehicles in motion and stopped vehicles.

Considering the approaching vehicles as a queue, we split capacity improvement process into two stages. First, the purpose is to make sure more vehicles in motion can pass through the as possible as they can. This makes sure these vehicles will not have to stop (i.e., due to a red light). Second, to make sure all the stopped vehicles can pass through the intersection in the next green phase as fast as they can. Here we can optimize the positions for stopped vehicles to achieve minimum delays when they pass through the intersection, which means at a fixed time period (for instance, a cycle length), the throughput is largest. In other words, we improve the throughput again.

In order to simplify the problem and better demonstrate the benefits of CV, one lane is used as shown in Fig. 1. Each vehicle is equipped with an on-board equipment (OBE), which can obtain the speed and location information of the vehicle. There is roadside equipment (RSE) by the intersection, which broadcasts the signal phase and timing (SPaT) of the local intersection. Using V2I communication, real-time data, including speed and location, can be sent from the vehicles to the RSE. Meanwhile, the SPaT data, such as remaining green time, can be delivered from the RSE to the vehicles. Next, the method of maximizing the throughput and minimizing the total delay of *n* vehicles is presented.

3. CONNECTED VEHICLE-BASED THROUGHPUT OPTIMIZATION ALGORITHM

In this section, the main steps of the proposed algorithm are developed. There are two main processes in this method: (1) optimization for vehicles in motion, and (2) optimization for stopped vehicles. The first one is used to maximize the intersection throughput of vehicles in motion via advisory acceleration. The second one is to minimize the total delay of the stopped vehicles by adjusting stopped vehicles' positions.

3.1 Optimization for vehicles in motion

In order to maximize the throughput of intersection *A* (Fig. 1) during a green phase, providing an advisory speed to vehicles is used to optimize the cut-off of the traffic stream. With CV technology, we can obtain two types of data: the speed v_i and location x_i of each vehicle i (Guler et al., 2014). Using the location of each vehicle, the distance l_i between the vehicle and the center of the intersection can be calculated. In addition, the SPaT data, such as remaining green time g, of the intersection can also be captured (Ding et al., 2013). In order to maximize the throughput, we need to minimize the following objective function:

[1] $$\min \quad n = \sum_{i=1}^{N} b_i$$

where, n is the number of vehicles stopped at the intersection when the phase switches to beginning of the red phase, and $b_i \in \{0,1\}$ is an integer indicating that car i stops before the intersection ($b_i = 1$) or does not stop ($b_i = 0$). In this objective function, smaller n means a smaller *1* in the summation function, which means more vehicles do not stops and pass through the intersection.

Considering the speed profile, there are two possible outcomes for a vehicle based on the recommended speed: passing through the intersection or not. The first case is that the vehicle cannot pass through the intersection, even if speeding up to the speed limit. In this case, the vehicle must stop. The second case is the vehicle can pass through the intersection by speeding up to an appropriate speed (not exceeding the speed limit), or by maintaining the current speed. Because of existing speed limits, the speed constraint for green phase can be formulated as follows using basic kinematic laws:

[2] $$\begin{aligned} &\left(\frac{l_i - \frac{v_{\max}^2 - v_{i,0}^2}{2a}}{v_{\max}} + \frac{v_{\max} - v_{i,0}}{a}\right) - g <= (1 - y_i) * M, \\ &-(b_i - 1) <= y_i * M, \\ &a <= a_{\max}, \\ &b_i, y_i \in \{0,1\}; \quad i \in \{1, \ldots, N\}. \end{aligned}$$

where, l_i is the distance between vehicle i and intersection j; g is the remaining green time for current intersection; v_{max} is the speed limit for the current road; $v_{i,0}$ is the original speed; a is the acceleration rate; a_{max} is the maximum acceleration rate; y_i and M are redundant variables for problem formulating, which can convert the *if-then* constraints to normalized optimization form and solving them by some standard algorithms, such as the branch-and-bound algorithm. M is large enough here. The following are the original straightforward *if-then* constraints based on basic kinematic laws:

[3] $$\begin{aligned} &if \quad \frac{l_i - \frac{v_{\max}^2 - v_{i,0}^2}{2a}}{v_{\max}} + \frac{v_{\max} - v_{i,0}}{a} < g, then \qquad b_i = 0 (\text{if} - \text{then} \qquad \text{constrain}) \\ &a <= a_{\max}, \\ &b_i, y_i \in \{0,1\}; \quad i \in \{1, \ldots, N\}. \end{aligned}$$

Here, if a vehicle i is following the advisory speed and the travel time to pass through the intersection is less than the remaining green time g, this vehicle will not have to stop and the corresponding b_i is zero. Though equation (2) is formulated for when the signal is in green phase, it is straightforward to derive similar constraints for when the signal is in red phase. Here, the green phase scenario is used to illustrate.

3.2 Optimization for stopped vehicles

Following equation (1), there are n vehicles stopped during the red phase and the assumption is that they will pass through during the next green phase. As all approaching vehicles are stopped slowly when drivers face the red phase, this will create the jam density. When the signal switches from red to green, each vehicle will start to accelerate to free flow speed, one vehicle at a time. The reason why each vehicle needs to accelerate one by one is that the headway between two consecutive vehicles is too small. The downstream vehicle needs to wait for the upstream vehicle to move far enough ahead before it can start to move forward (Oglesby and Hicks, 1982). For example, the n^{th} (the last) vehicle needs to wait *n-1* times of an average acceleration delay waiting for previous *n-1* vehicles before it can accelerate. If several vehicles can start to accelerate at the same time, the total delay will decrease. By optimizing the space headway between two consecutive vehicles, it is possible to let several vehicles start moving at the same time. The objective function can be expressed as follows:

[4]

$$\min \overbrace{\sum_{i=1}^{n}(\max(\frac{-a*\frac{1}{s_m}*(i-1)+\sqrt{[a*\frac{1}{s_m}*(i-1)]^2+2*a*L_{in}}}{a},\frac{L_{in}}{v_{\max}}))}^{previou\ total\ delays}$$

$$-(\overbrace{\underbrace{\sum_{i=P+1}^{n}(\max(\frac{-a*\frac{1}{s_m}*(i-P-1)+\sqrt{[a*\frac{1}{s_m}*(i-P-1)]^2+2*a*L_{in}}}{a},\frac{L_{in}}{v_{\max}}))}_{non-optimized\ vehicles'\ delays}+\underbrace{(\frac{L_{in}}{v_{\max}}+\frac{1}{s_m}*(\mathrm{P}-1))}_{optimized\ vehicles'\ delays}}^{current\ total\ delays}$$

where, a is the acceleration rate; s_m is the saturation rate; i is the stopped vehicle index; L_{in} is the length of the intersection; v_{max} is the speed limit of that road; p is the stopped vehicle index whose headway is optimized; and P is the maximum number of optimized vehicles. Here, the decision variable is the number of the optimized headway vehicles. As shown in the equation (4), the previous total delays minus the current total delays is the objective function. In term of the current total delays, this function is composed by the delays of the non-optimized vehicles and optimized vehicle's delay. It is straightforward the time headway of the optimized vehicles have is time headway corresponding to the saturation flow. In order to get the delay time of the non-optimized vehicles' delays t_i for vehicle i, we use the following equation (5) based basic kinematic laws when vehicles pass through the interactions.

[5]

$$L_{in}=\frac{1}{2}at_i^{\,2}+a*\frac{1}{s_m}*(i-1)*t_i$$

$$or \qquad L_{in}=v_{\max}t_i$$

where, we use the kinematic laws to calculate the delays when the vehicle passes through the intersection with an advisory acceleration ratio a. When the vehicle passes through the intersection, the speed can be $a*\frac{1}{s_m}*(i-1)$ or v_{max} because of the existing posted speed v_{max}.

The main constraint is the current number of approaching vehicles and the length of the segment, which can be shown as the following:

[6]

$$L_{seg}-\frac{n}{k_m}+\frac{P}{k_m}<=P*\frac{1}{s_m}*v_{\max},$$

$$L_{seg}-\frac{n}{k_m}>=0,$$

$$n,i,p,P\in N^{+},$$

where, L_{seg} is the length of the road segment; k_m is the jam density of the road segment; and n is the current number of approaching vehicles. The term $L_{seg}-\frac{n}{k_m}+\frac{P}{k_m}<=P*\frac{1}{s_m}*v_{\max}$ is used to make sure the space headway between two consecutive vehicles is safe enough to start moving forward. Another term $L_{seg} - \frac{n}{k_m} >= 0$ is defined to make sure there are some redundant space at the end of the stopped vehicle queue to be used for optimizing the position of the vehicles.

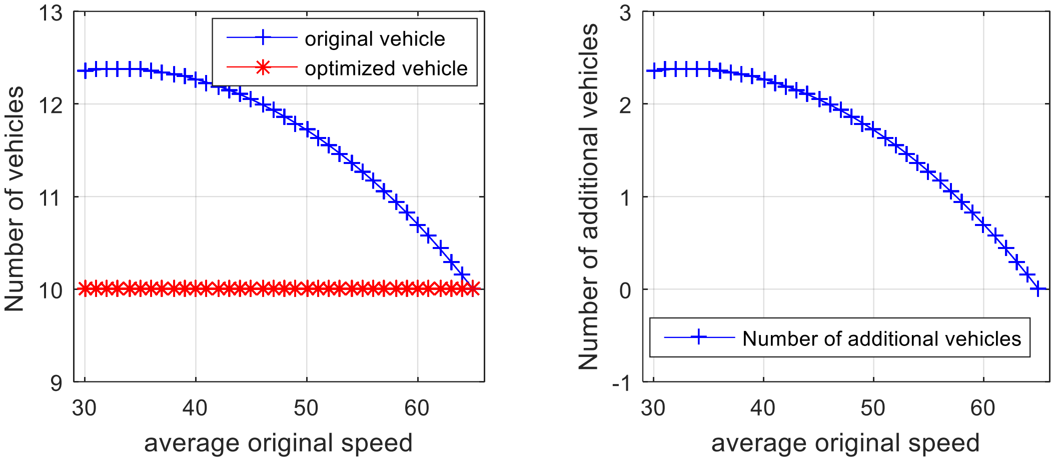
Here, by optimizing the headways of the vehicles at the queue beginning, there will be P vehicles starting at the same time. This means P vehicles will start accelerating with the same acceleration rate as calculated by the RSE, because there is enough space for them to accelerate from zero simultaneously. Technically, this strategy can be achieved by using vehicle-to-infrastructure (V2I) communication. With V2I, each vehicle will receive location information determining where it needs to be stopped before it faces the next green phase. After the positions of the selected P vehicles are optimized, the vehicles can move in synchronization as a single vehicle because of enough existing headway space. When the signal phase switches to green, P vehicles can accelerate at the same time, which will reduce the releasing delay for the whole queue.

4. EVALUATION AND ANALYSIS

Numerical calculation is used to demonstrate the performance of the proposed optimization methodology. All calculations are conducted using MATLAB. The speed limit is 65 km/h; the saturation flow is 1800 veh/h; the length of the segment is 500 meters; assuming there is one lane and lane width is 12 meters; and the jam density is 200 veh/km (Transportation Research Board, 2010). The acceleration rate is decided by the current speed and is calculated (Maurya and Bokare, 2012) using the following equation:

[5] $$acc = 1.70e^{-0.04v}$$

where, v is the average original speed of a considered vehicle.

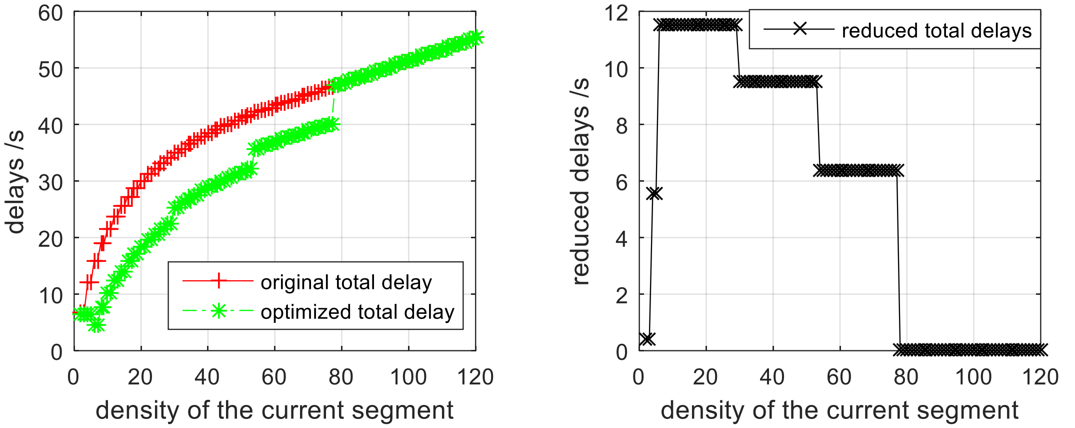


(a) Number of vehicles that passed through the intersection

(b) Number of additional vehicles

Figure 2: Throughput Improvement of Vehicles in Motion

As shown in both Figure 2(a) and 2(b), the benefits of more vehicles in motion being able to pass through intersection A are shown. From the Figure 2(a), we can see that for different average speeds of approaching vehicles, the optimized number of vehicles passing through is larger than the original non-optimized number if the vehicles can accelerate to the maximum allowable speed, i.e., the posted speed limit. Thus, throughput will be increased. From Figure 2(b), when the average original speed is low, the benefit is that more vehicles can pass through the intersection.



(a) Total delays of the stopped vehicles (b) Reduced total delays of the proposed method

Figure 3: Total Delay Results of the Stopped Vehicles

As shown in Figure 3(a) and 3(b), both the total delays and benefits of the proposed method are shown. From the Figure 3(a), we can see that for different densities of the current segment, the optimized total delay is smaller than the original total delays when the headway of some vehicles is optimized. This means at a fixed time period, the throughput is largest. In other words, the throughput is improved. From Figure 3(b), we can see that with the increase of the density, the benefits keep no increases because of no enough spaces for position adjustment.

CONCLUSION

This paper proposes a CV-based approach to improve the throughput at signalized intersections and thereby increase the mobility of a transportation system. The proposed approach takes advantage of real-time data to develop a strategy that maximizes the throughput of an isolated intersection. Accordingly, the problem is modeled as a two-step centralized optimization problem, which can optimize the vehicles in motion and stopped vehicles simultaneously. A case study is also presented to show the efficiency of the proposed approach. From the results, we can see that for different average speeds of current vehicles, throughput will increase if vehicles can accelerate to the maximum allowed speed. Also, by assigning vehicles optimized headways, the total delay is reduced. That means the proposed method can improve traffic flow throughput of intersections and reduce the total delay of all vehicles. However, as shown in the optimization formulation part, there are some limitations in this study. In optimization for vehicles in motion, the average speed of the vehicle in motion is critical and high vehicle speeds mean fewer benefits are obtained. In optimization for stopped vehicles, the greater the density of traffic flow, the fewer the benefits, which means this method can have limited performances in large density scenarios. In the future, more works using optimization methodology will explore improving the throughput with greater speeds and densities.

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