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Car2X Technology–based "Green Light on Demand" System*

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***Abstract*— Car2X technology helps obtain information about individual vehicles, which acts as an accurate data resource for determining traffic status from the viewpoint of a traffic signal controller designing phase timing. Based on Car2X technology, a prototype system for "Green Light on Demand," which means adapting traffic signal automatically for privileged vehicles if necessary, is developed. Two types of passing algorithms for privileged vehicles at a single intersection are proposed. The first algorithm was tested by conducting a field experiment, and the result demonstrates that the system can reduce the number of stops for privileged vehicles. The second algorithm was tested in a simulation experiment, the results of which prove that the signal control algorithm can reduce the travel time and number of stops for privileged vehicles, while not having any significant effect on normal vehicles.**

I. Introduction

With car ownership in China increasing every year, the occurrence of traffic jams is increasing in frequency, which causes problems for privileged vehicles that need to pass intersections quickly without delay. Although these vehicles can violate traffic signals according to Road Traffic Act in China, this priority cannot be guaranteed owing to traffic jams. Besides, the pass of privileged vehicles may lead to traffic jams especially in China where there are many aggressive drivers that may not avoid privileged vehicles, so the travel efficiency of normal vehicles must be taken into account during the passing of privileged vehicles in case of the occurrence of traffic jams.

Considerable research effort has been dedicated toward solving this problem. Hall T J[1] proposed a global positioning system–based emergency vehicle preemption system which uses communication devices for information broadcasting. Eric J. Nelson[2] evaluated three types of signal transition strategies for emergency vehicle signal preemption. Ilsoo Yun[3] investigated exit phase control for emergency vehicle preemption. Xiaolin Qin[4] proposed a two-stage signal transition strategy for emergency vehicles. Song Huihua[5] proposed a signal preemption system for emergency vehicles based on the multi-agency technology. Yinsong Wang[6] designed an emergency vehicle signal priority system in a cooperative vehicle-infrastructure system environment. Kwon E L[7] designed a route-based signal preemption strategy using Dijkstra's algorithm to provide the most efficient and safe route for emergency vehicles. Nesrin Basoz[8] developed a geographic information system (GIS)–based emergency response network analysis program for post-earthquake traffic routing. Casturi R[9] presented a macroscopic traffic model for examining the effect of signal preemption for emergency vehicles based on the cell transmission model. Houng Y. Soo[10] developed a decision support system framework and the corresponding analytical tools to assess the effects of advanced traffic signal control systems capable of integrating emergency vehicle preemption and transit signal priority operations for investment planning purposes. Gartner N. H.[11] proposed a signal timing strategy setting weights for public bus to minimize per capita delay. Xiaoguang Yang[12] proposed design methods of transit priority signal at signalized intersection.

In recent years, there has been rapid advancement in the Car2X technology, which is used for building communication channels between vehicles and infrastructure, and providing more accurate information about individual vehicles to the traffic signal controller than traditional vehicle detection technology. Based on the Car2X technology, a prototype of a "Green Light on Demand" system is developed. This system automatically adapts traffic signals for privileged vehicles if necessary. By using information about privileged vehicles, the traffic signal control algorithm can be optimized to reduce delay for privileged vehicles and improve their travel efficiency.

II. System Configuration

A. System Function

In the system, a privileged vehicle is equipped with dedicated short range communication (DSRC) devices, which broadcast vehicle information such as longitude, latitude, velocity, course angle, and priority. Simultaneously, normal vehicles can be detected using detectors deployed around intersections.

When a privileged vehicle arrives at an intersection and the distance between the vehicle and the traffic light is within the communication range, the traffic signal controller will receive a priority request from the privileged vehicle. Considering the time required for the queue of vehicles before the privileged vehicle to dissipate, the system transmits the signal for the privileged vehicle beforehand to guarantee that the privileged vehicle can pass the intersection without stopping, as well as minimize the impact on normal vehicles.

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B. System Structure

The system structure includes two parts: onboard hardware and roadside hardware.

1) Onboard Hardware

Onboard hardware on the privileged vehicle comprises a Denso WSU (wireless safety unit, a kind of communication device based on DSRC protocol), GPS module, and computer. A schematic diagram of the onboard hardware setup is shown in Figure 1.

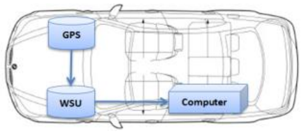

Figure 1. Onboard Hardware Setup

2) Roadside Hardware

Roadside hardware on the traffic signal light consists of a lower signal controller, Denso WSU, GPS module (actually when the traffic light is static, the GPS module is unnecessary), and computer, which serves as the upper signal controller. A schematic diagram of the roadside hardware setup is shown in Figure 2.

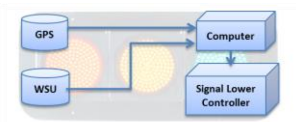

Figure 2. Roadside Hardware Setup

3) Information Flow

Information flow between a privileged vehicle and the signal control system is shown in Figure 3. Here the upper signal controller is a computer for data procession and the lower signal controller is a microprocessor for signal switching operation.

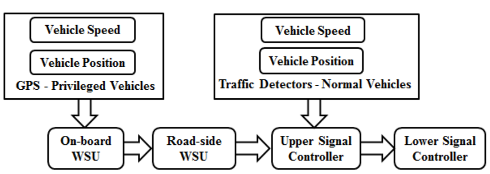

Figure 3. Information Flow

III. Passing Algorithm Design

A. Vehicle Detection Method

The passing algorithm is based on vehicle information. Information about privileged vehicles can be gained easily from the on-board communication devices. However, for normal vehicles, which do not have said communication devices, detectors are needed to obtain the required information.

Detectors are arranged in each lane at each entrance of the intersection before the stop line, and the distance between each detector in a given lane is D_0. Detector arrangement, for example, for a single-lane intersection is as shown in Figure 4. The detectors are denoted by d_{ij} (i denotes entrance number, and j denotes detector number).

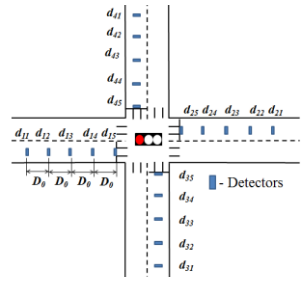

Figure 4. Detector Arrangement

A counter is set in each detector to calculate the number of vehicles that pass it, and the number is denoted as n_{ij}. Additionally, the velocity of the last vehicle that passed the detector is recorded, and it is denoted as v_{ij}.

Thus, the number of vehicles in a lane segment between two adjacent detectors, denoted as d_{ij} and d_{ij+1}, is given as follows:

$$N_{ij} = n_{ij} - n_{ij+1}, i, j = 1,2,3,4 \quad (1)$$

The locations of these vehicles are hard to obtain, so here we suppose that these vehicles are equally spaced between the two detectors d_{ij} and d_{ij+1}, the distance between a vehicle instance k and the stop line is as follows:

$$L_{ijk} = (5-j)D_0 - k\frac{D_0}{N_{ij}}, k = 1,2,3,..., N_{ij} \quad (2)$$

The vehicle index k starts from the farthest vehicle from the stop line, and increases towards it. And the "5" is the number of detectors.

The velocities of these vehicles are hard to obtain, so we estimate them with the mean velocities of the last vehicles passing the limiting detectors:

$$V_{ij} = \frac{v_{ij} + v_{ij+1}}{2}, i, j = 1,2,3,4 \quad (3)$$

Based on information collected from the privileged vehicle and normal vehicles near the intersection, two types of passing algorithms are proposed using different signal control methods.

B. Passing Algorithm based on Mathematical Analysis Method

In this algorithm, we formulate mathematically the conditions under which a privileged vehicle can pass the intersection without stopping. Here, we set the time at which a signal controller receives a priority request from a privileged vehicle as zero hour.

1) Condition for vehicles passing an intersection

At first, we describe the condition for judging whether a vehicle can pass the intersection before the privileged vehicle arrives at the intersection.

Consider that the velocity of a vehicle approaching an intersection for a vehicle instance k is V_k, and the distance between the vehicle and the stop line is L_k. Thus, the condition for the vehicle to pass the intersection is as follows:

$$t_k = \frac{L_k}{V_k} \in (g_i, r_i), i \geq 1 \tag{4}$$

where g_i and r_i denote the time at which a green phase starts and ends, respectively, as shown in Figure 5. The two diagrams show different situations with regard to the current signal state where the definitions of g_i and r_i are different.

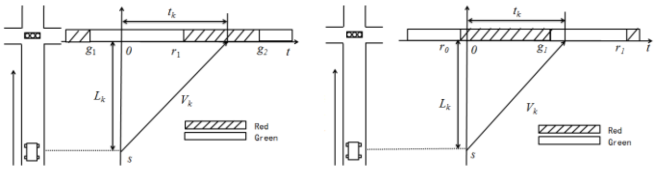

Figure 5. Condition for a vehicle to pass an intersection

2) Dissipation Delay

The vehicles that cannot pass the intersection before the privileged vehicle arrives are made to wait in a queue, which may stop the privileged vehicle.

To calculate the time required for the queue to dissipate, we assume that these vehicles are equally spaced before the stop line, the space headway is l_0, and vehicle length is d_0, as shown in Figure 6. Furthermore, it is assumed that the delay from the time when the traffic light turns green to the time when the first vehicle in the queue starts to accelerate is Δt_1. The delay from the time when a vehicle starts to accelerate to the time when the vehicle behind it starts to accelerate is Δt_2, and the vehicles move with a constant acceleration a_0 until their velocity reaches a constant value v_0, as shown in Figure 7.

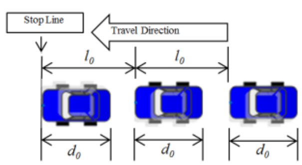

Figure 6. Space Relationship during Starting Process

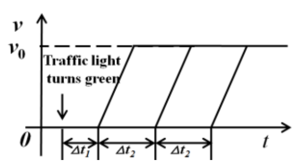

Figure 7. Velocity Curves during Starting Process

Therefore, for a queue with n vehicles, the dissipation delay from the time when the signal turns green to the time when the last vehicle passes the stop line is as follows:

$$\begin{aligned} T_d(n) &= \Delta t_1 + (n-1)\Delta t_2 + \frac{v_0}{a_0} + \frac{(n-1)l_0 + d_0 - \frac{v_0^2}{2a_0}}{v_0} \\ &= \Delta t_1 + (n-1)\left(\Delta t_2 + \frac{l_0}{v_0}\right) + \frac{v_0}{2a_0} + \frac{d_0}{v_0} \end{aligned} \tag{5}$$

3) Condition for privileged vehicle to pass intersection without stopping

Above all, the dissipation delay can be calculated according to the number of vehicles in the queue that cannot pass the intersection before the privileged vehicle arrives at the intersection. Here, the velocity of the privileged vehicle is v_E, and the distance between the privileged vehicle and the stop line is l_E. Therefore, the time at which the privileged vehicle arrives at the intersection is denoted as $t_E = l_E/v_E$, and the condition for privileged vehicle to pass the intersection without stopping is given as follows:

$$[t_E - T_d, t_E] \subset [g_i, r_i], i \geq 1 \tag{6}$$

4) Algorithm Design

For the two directions of the intersection, the green-phase lengths are denoted as G_1 and G_2. We traverse G_1 and G_2 from the minimum green-phase period $G_{\min}$ to the maximum green-phase period $G_{\max}$ in steps of Δt:

$$G_i = G_{\min}, G_{\min} + \Delta t, G_{\min} + 2\Delta t, ..., G_{\max}, i = 1, 2 \tag{7}$$

For each combination of G_1 and G_2, we get a signal-timing strategy. For a signal-timing instance k denoted as ST_k, we calculate the number of vehicles n_k that cannot pass the intersection before the privileged vehicle arrives at the intersection, and the time required for the queue to dissipate is $T_d(n_k)$. Then, using the condition for a privileged vehicle to pass the intersection without stopping, we determine whether the privileged vehicle can pass the intersection without stopping.

For each signal-timing strategy, according to the condition for vehicles passing an intersection and the condition for privileged vehicle to pass intersection without stopping above, we can calculate the number of stops of the privileged vehicle and normal vehicles, which are respectively denoted as N_{EV} and N_{NV}. Therefore, the performance index of a signal-timing strategy can be denoted as follows:

$$PI = N_{EV} l_{N-EV} + N_{NV} l_{N-NV} \tag{8}$$

where l_{N-EV} and l_{N-NV} are lost coefficients. Thus, the lower the performance index PI, the better is the signal-timing strategy.

The flow chart of the algorithm is shown in Figure 8.

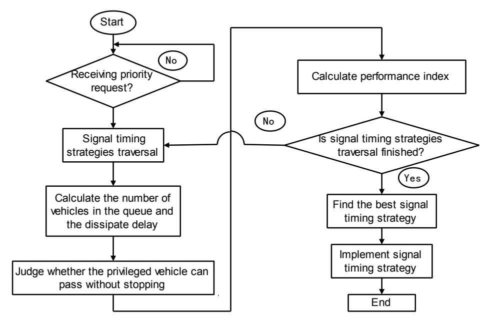

Figure 8. Flow Chart of Passing Algorithm based on Mathematical Analysis Method

C. Passing Algorithm based on Modeling and Simulation Method

Microscopic traffic simulation helps predict the traffic status, which is required for evaluating signal phase timing strategies to find the optimal strategy. Here, we use the **cellular automata model**, which is based on a fixed update rule and discrete status of time and space, as the simulation method. This method helps reduce the computational cost and allows for online calculations.

1) Cellular Automata Model

In the passing algorithm, we use a single-lane cellular automaton model at a signalized intersection derived from the Na-Sch model[13] in the traffic flow microscopic simulation. In the model, lane changes, turning, and overtaking by the vehicles are not considered. The vehicle status update rule is as follows:

a) Acceleration Step:

For a vehicle instance *n*, it tends to run at a high velocity, so it will accelerate by steps:

$$v_n \to \min\left(v_n + 1, v_{\max}\right) \tag{9}$$

where v_n is the velocity of vehicle *n*, v_{max} is the maximum velocity of the vehicle.

b) Deceleration Step:

If the signal ahead of vehicle *n* is red or if the cells after the stop line of the intersection are occupied by other vehicles,

$$v_n \to \min\left(v_n, d_n, s_n\right). \tag{10}$$

Else,

$$v_n \to \min\left(v_n, d_n\right). \tag{11}$$

where d_n is the distance between vehicle *n* and the vehicle in front of it, and s_n is the distance between vehicle *n* and the stop line in front of it.

c) Randomization Step:

With the probability *p* ($0 \leqslant p \leqslant 1$) vehicle *n* will decelerate randomly:

$$v_n \to \max\left(v_n - 1, 0\right) \tag{12}$$

d) Movement Step:

Vehicle *n* will run with the updated velocity v_n:

$$x_n \to x_n + v_n \tag{13}$$

where x_n is the displacement of vehicle *n*.

2) Algorithm Design

Simulations are initiated based on information about current traffic status. In the algorithm, the length of the green phase will also be **traversed** from the minimum green phase period G_{min} to the maximum green phase period G_{max} in steps of Δt, according to expression (7). The simulation is implemented for each signal-timing strategy.

The signal-timing strategies are evaluated based on the simulation result. Here, we denote the number of stops and delay of the privileged vehicle as N_{EV} and T_{EV}, respectively, and the number of stops and delay of normal vehicles as N_{NV} and T_{NV}. Therefore, the performance index of a signal-timing strategy can be expressed as follows:

$$PI = N_{EV} l_{N-EV} + T_{EV} l_{T-EV} + N_{NV} l_{N-NV} + T_{NV} l_{T-NV}, \tag{14}$$

where l_{N-EV} and l_{T-EV} are lost coefficients of privileged vehicles respectively for the number of stops and the time delay, while l_{N-NV} and l_{T-NV} are lost coefficients of normal vehicles. Thus, the lower the performance index *PI*, the better is the signal-timing strategy.

The flow chart of the algorithm is shown in Figure 9.

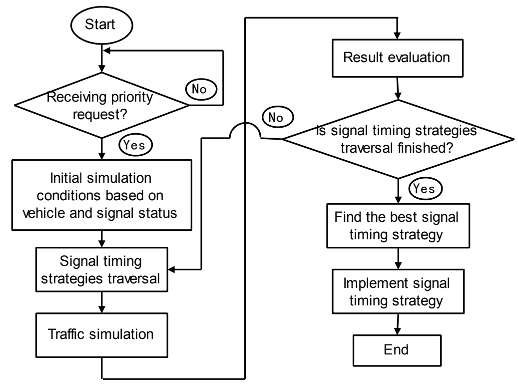

Figure 9. Flow Chart of Passing Algorithm based on Modeling and Simulation Method

IV. Road Experiment Based on First Passing Algorithm

A. Experiment Conditions

An experiment is conducted based on the first passing algorithm in Langfang, China. Three vehicles are used in this experiment. To simplify the experiment, all three vehicles are equipped with communication devices instead of being detected by traffic detectors. To compensate for the lack of vehicles, we simply consider the traffic efficiency of the privileged vehicle.

The experiment consists of three test cases, as shown in Figure 10.

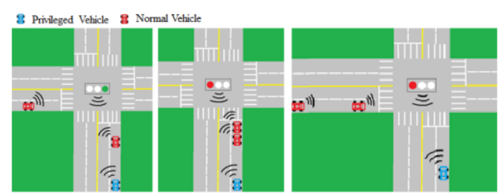

Figure 10. Test Cases

B. Experiment Results

For every test case, the experiment is repeated 10 times under the same conditions. In all test cases, the privileged vehicle can pass the intersection without stopping, which contributes to reducing the time delay and improving the travel efficiency of the privileged vehicle.

V. Simulation Experiment Based on Second Algorithm

Based on the second passing algorithm, a simulation experiment is implemented in VISSIM. VISSIM offers users the component object model (COM) for accessing the simulation model and data to dynamically modify the signal phase timing. In addition, a signal control system co-simulation platform is built using Visual Basic.NET. The platform structure is shown in Figure 11.

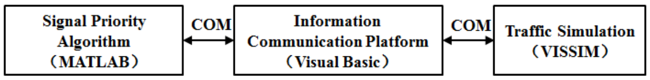

Figure 11. Structure of Co-simulation Platform

A. *Simulation Conditions*

In the simulation experiment, a single-intersection model is built in VISSIM. The intersection layout in the model is shown in Figure 12. The two directions of the intersection are identical with equal traffic flow inputs. Five detectors are arranged at each intersection entrance with an equal special interval of 30 m, and the privileged vehicle is deployed in the east–west direction.

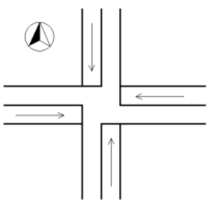

Figure 12. Intersection Layout

In the simulation experiment, control experiments were carried out to compare the two phase-timing strategies: fixed signal phase timing and green light on demand phase timing. Considering the traffic flow, five groups of contrast simulations are implemented with various traffic flows ranging from 400 vehicles per hour to 800 vehicles per hour. Moreover, in each group of experiments, the simulation is repeated 10 times with different initial random seeds, and the average of the 10 readings is considered as the final result.

B. Simulation Results

The average number of stops and delay of the privileged vehicle (PV) are listed in Table I and shown in Figure 13. ("F" denotes fixed phase timing and "G" denotes Green light on demand signal timing.)

TABLE I. AVERAGE NUMBER OF STOPS AND DELAY OF PV

Traffic Flow (veh/h)	**Signal Timing**	**Average Number of stops**	**Average Delay(s)**
400	F	0.5	10.9
	G	0.1	1.7
	±%	80.0%	84.4%
500	F	0.8	23.3
	G	0.2	4.6
	±%	75.0%	80.3%
600	F	0.8	26.2
	G	0.1	3.5
	±%	87.5%	86.6%
700	F	0.8	21.8
	G	0.2	5.3
	±%	75.0%	75.7%
800	F	0.7	23.9
	G	0.4	11.4
	±%	42.9%	52.3%

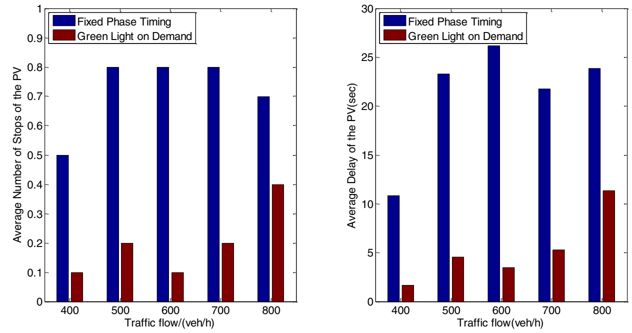

Figure 13. Average number of stops and delay of PV

The average number of stops and delay, as well as the queue length of normal vehicles (NVs), are listed in Table II and shown in Figure 14-16("F" denotes fixed phase timing, "G" denotes Green light on demand signal timing, and "EW" and "NS" denote the east–west and north–south directions, respectively; the privileged vehicle is along the east–west direction). From the simulation results, we can draw the following conclusions:

1) The green Light on demand signal phase timing strategy can help reduce the average number of stops and delay of the privileged vehicle by more than 42% at least under the various traffic flow conditions employed in the simulation. This is because the algorithm will find out and execute signal phase timing strategies that allow the privileged vehicle to pass without stop when they exist. And the optimal effect depends on the accuracy of the estimation of vehicles' locations and velocities.

2) The optimal effect of the green light on demand system is influenced by traffic flow and the average number of stops and delay of the privileged vehicle increase as the traffic flow increases. Actually when the traffic is very busy, for example when the length of vehicle queue is larger than the communication range, it's impossible for normal vehicles to dissipate before the privileged vehicle arrives even if the light is locked in green phase at the time the priority request is received by the signal controller.

3) For normal vehicles, the average number of stops and delay, as well as queue length, can be generally reduced compared with that achieved using fixed phase timing. This is because the algorithm will find out and execute the optimal signal phase timing strategy to realize the best performance index mentioned above with the information of vehicles, while for a fixed phase timing strategy only the statistic data information like the traffic flow is used.

4) The average number of stops and delay, as well as queue length of vehicles, in the north–south direction is greater than that of the vehicles in east–west direction. That is the tradeoff of the Green Light on Demand signal timing: the normal vehicles have a higher chance to pass the intersection without stop when the privileged vehicle approaches in the same direction, while those in the other direction may be delayed for the privileged vehicle. This causes the difference of the passing efficiency for vehicles in different directions. However, the difference is not very large, which means that the effect on normal vehicles is not major.

TABLE II. AVERAGE NUMBER OF STOPS AND DELAY OF NVS

Traffic Flow (veh/h)	Signal Timing	Average Number of stops		Average Delay (s)		Average Queue Length (m)	
		EW	NS	EW	NS	EW	NS
400	F	0.65	0.63	15.6	14.6	9.2	9.7
	G	0.54	0.69	12.2	16.4	7.9	10.8
500	F	0.77	0.67	18.6	16.5	15.0	12.7
	G	0.64	0.68	17.0	14.9	13.5	11.7
600	F	0.72	0.89	17.7	19.4	15.5	18.4
	G	0.80	0.80	17.9	15.6	16.4	13.3
700	F	0.95	0.95	20.7	19.5	22.5	21.2
	G	0.82	0.92	16.5	18.4	17.3	18.9
800	F	1.17	1.34	23.6	23.0	29.0	29.6
	G	1.07	1.26	23.1	18.4	30.6	19.9

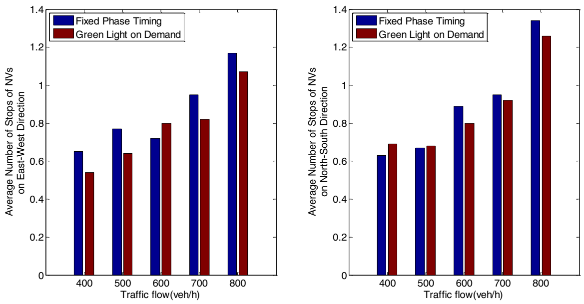

Figure 14. Average number of stops of NVs

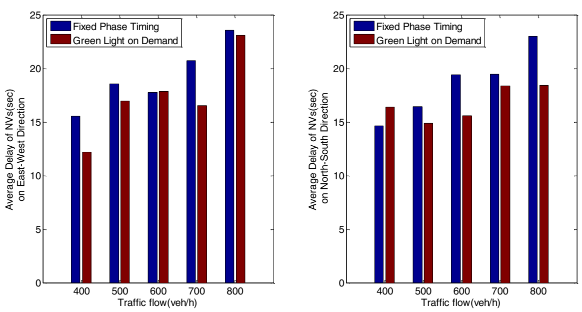

Figure 15. Average delay of NVs

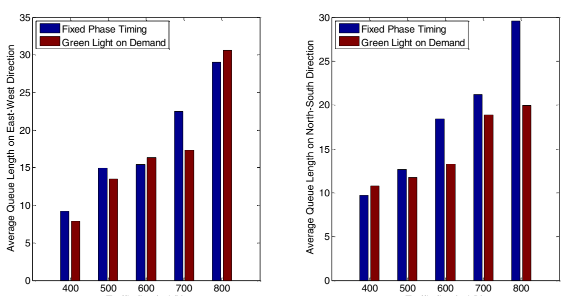

Figure 16. Average Queue Length of NVs

For the algorithm, if we don't distinguish between privileged vehicles and normal vehicles, that is: $l_{N\text{-}EV} = l_{N\text{-}NV}$, and $l_{T\text{-}EV} = l_{T\text{-}NV}$, it will become a signal timing algorithm that can reduce traffic delay under regular traffic situations. Or if there are more than when one privileged vehicles, we can simply change the value of lost coefficient to give them different priority levels. Above all, we can change the performance index for different kinds of management goals and the algorithm will work in these situations.

VI. CONCLUSIONS

In this paper, a Car2X technology–based "Green Light on Demand" system is established and two types of passing algorithms are proposed. The first algorithm based on kinematical analysis is tested in a real-road test, which shows that the system helps privileged vehicles pass without stops under the test conditions. The second algorithm uses cellular automata for traffic modeling and simulation and is tested in a simulation test, which proves that the system can help reduce the average delay and number of stops by more than 42% for the privileged vehicle under the various traffic flow conditions in the experiment, while not having any significant effect on normal vehicles.

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