# VEHICLE PRIORITY SCHEDULING USING VEHICLE-TO-INFRASTRUCTURE COMMUNICATIONS

**William E. Alexander**
Corresponding Author
Department of Civil, Architectural, and Environmental Engineering
The University of Texas at Austin**
Tel: +1-256-656-7723 Fax: N/A Email: wealexander@utexas.edu

**Alexander M. Hainen**
Department of Civil, Construction, and Environmental Engineering
The University of Alabama
Tel: +1-256-348-3139 Fax: +1-205-348-6862 Email: ahainen@eng.ua.edu

**Xiaoyan Hong**
Department of Computer Science
The University of Alabama
ORCiD: 0000-0002-0745-5038
Tel: +1-205-348-4042 Fax: +1-205-348-0219 Email: hxy@cs.ua.edu

Word count: 6,302 words

Submission Date: 2018-08-01

** Author W.E. Alexander's contributions occurred while a part of the Department of Computer Science at The University of Alabama.

## ABSTRACT

Vehicle-to-Infrastructure communications offer great opportunities for developing applications for Intelligent Transportation Systems with real-time vehicle motion information. In this paper, we propose to leverage this technology in a system that reduces delay for a priority vehicle by adjusting an isolated, actuated traffic signal controller's timing mechanism in a non-invasive manner. We developed an algorithm and architecture that monitors connected vehicle location data and recent intersection performance, calculates a minimum-disruption timing plan which provides a green light to the priority vehicle at its arrival, if possible, then enforces the plan until the vehicle arrives. The algorithm and software architecture were tested in simulation, with results showing significant reduction in priority vehicle delay with little impact on traffic at the intersection. The work demonstrates the power of Vehicle-to-Infrastructure communication in enhancing transportation operation. The results show that, by temporarily enforcing a timing plan and modifying it to accommodate a priority vehicle's arrival, the delay the vehicle encounters at an intersection can be reduced without adding significant delay for other vehicles crossing said intersection. The simulation results we present indicate that this system could be deployed at an isolated intersection to dramatically reduce priority vehicle delay without significant detriment to the remaining vehicles utilizing the intersection. By extending this system with vehicle occupancy data, decision-making can be made autonomously as to whether, when, and how to facilitate a priority vehicle while minimizing impact to the rest of the operations at an intersection.

*Keywords*: Vehicle-to-infrastructure communication; intelligent transportation systems; traffic signal control; priority vehicles

# INTRODUCTION

With the advent of vehicle-to infrastructure (V2I) and vehicle-to-vehicle (V2V) technologies, vehicle information can readily be acquired by intelligent transportation systems (ITS) to support many applications that greatly contribute to travel safety, efficiency, and ease of use. For example, information about vehicle platoons can be collected by a traffic control center to optimize the traffic signal scheduling for higher efficiency (*1, 2*).

Generally, traffic signal controllers (TSC's) operate using a fixed-cycle timing plan, or they serve green time in response to demand from simple vehicle detectors in the roadway. More advanced systems often include a request server device to allow a priority vehicle, e.g. an ambulance, to shift the current signal phase to the vehicle's desired phase in an emergency (*3*). This priority method can invoke a dramatic divergence from a signal's predetermined timing plan and can cause large disruptions at intersections serving a traffic volume near or at its capacity. As connected vehicle technology becomes more ubiquitous, a system for intelligent priority using these tools can be developed. This system may coordinate a priority request with surrounding traffic and past performance to reduce the severity of the request's traffic flow disruption.

General traffic coordination using connected vehicle technology is a topic of great complexity, as shown in the works of Al-Khateeb et al. and Milanes et al. (*1*, *4*). Al-Khateeb et al. proposed early on to use RFID to dynamically control traffic lights (a simplified version of full V2I communication) and implements this strategy in simulation (*1*). Later work by Milanes at al. develops a full V2I-based traffic management and collision avoidance strategy which is tested successfully both in simulation and real-world trials (*4*). These works were based on a considerably high penetration rate of connected and autonomous vehicles compared to current conditions in modern transportation systems.

Work in the field of V2I-based scheduling can be considered in three parts: the use of V2I for vehicle arrival prediction, for transit priority, and for general traffic coordination. This work leans heavily on prior work in the field of vehicle arrival prediction (*5*). The work in this paper proposes a combined historical and real-time approach for predicting a vehicle's arrival, and simulates their method with significant results. This is an area of high concern for improving upon the detection abilities for traffic controllers, as the further penetration of V2I communication provides for more complicated intersection control strategies. For transit priority usage, V2I has been implemented in various cities and studied repeatedly, such as the work of Ahmed et al. and Hu et al. (6, *7*). These works tend to treat a priority vehicle as a distinct class from traditional traffic, usually with separate restricted lanes to accommodate this classification.

A more traditional approach using standard shared-lane configurations has been undertaken regarding the use of predictive capabilities for controlling coordinated, rather than isolated, intersections (*8*). This paper is similar in that it uses a vehicle predictor to accommodate priority buses faster at an intersection. However, recent developments concerning the use of V2I communication to achieve this are not explored, and a different method for phase modification is used, which utilizes the simpler Phase Hold and Force Off methods of phase control. Two additional studies (*9, 10*) explore similar assumptions made herein, but also restrict control to the green extension and red truncation methods of timing adjustment.

Balke et al. proposes to override a coordinated intersection's side-street service based primarily on vehicle arrival time and the pre-set coordination plan in place for the intersection's corridor (*8*). A similar approach involves treating coordinated phase starts as a pseudo-priority request (*11*). While this approach relaxes the assumption of isolated intersections to produce coordinated priority movements, it also does not consider exact or near-exact arrival time prediction. Similar research develops a model which considers a stochastic arrival time using an intricate optimization model (*12).*

This work expands upon the field and propose a path forward in the transition to achieving a more automated intersection such as that described by B. Yang et al. (*13*) or K. Yang et al. (*14*), while still accommodating manual driving as we are familiar with today. B. Yang et al. propose for an intersection to take control of a vehicle's acceleration and deceleration to avoid collisions in a more traditional intersection (*13*), whereas K. Yang et al. (*14*) focus on adjusting intersection departure periods based on density of connected and autonomous vehicles. Both papers simulate the strategies they propose with successful results.

# OBJECTIVE AND CONTRIBUTIONS

In this paper, our goal is to create a V2I-based system which can implement priority vehicle requests for an isolated intersection without causing substantial increase in delays. Our objective is to implement an algorithm to allot green time to future phases based on recent performance, and later to adjust unused green time for phases so as to minimize the priority vehicle's delay (*8*), based on real-time vehicle location data obtained through an architecture which utilizes V2I communication. We concern ourselves in this work solely with isolated, non-coordinated intersections to provide flexibility in timing plan choice, as coordinated plans offer little room for timing plan modification. Our system includes vehicle location data reporting and collection via V2I, i.e. an onboard unit (OBU) sending data to a roadside unit (RSU), TSC traffic response monitoring, and phase planning algorithms.

This system is tested in a lab setting where V2I communications and TSC command and control are tested through simulation, separate from testing using real road segments and vehicle movements. The PTV VISSIM traffic simulation software we utilize includes a virtual TSC. A V2I-enabled priority vehicle was created in the simulation environment, in the form of a pre-generated bus whose arrival time and destination can be manipulated and therefore predicted with a high degree of certainty. A foundational assumption is made that well-defined, predictable arrival times are available for the priority vehicle. While this does not necessarily reflect the current state of the art, additional research into this field is ongoing and as market penetration of V2I-enabled vehicles grows, this assumption will become less restrictive in the near future. Additionally, while the industry standard service request protocol is not implemented in its entirety, the core concepts are replicated to relay V2I priority request communication. The algorithm's operation depends on interfacing with the intersection controller using its built-in NTCIP interface to establish a short-term signal timing plan, and on maintaining a model of prior intersection behavior created from the high-resolution signal phase and timing logs created by the TSC.

Typically, for non-emergency priority vehicles (NEPV), e.g. a transit bus, there is the desire to limit the priority vehicle's delay. Thus, a balance should be strived for, weighing this against the increased delay incurred by non-priority vehicles as a result of the request. To do this, adjustments to the controller's timing plan should factor in the green times allotted by the controller in previous cycles. Deviation from these values should be minimized so as to reflect as closely as possible the optimal intersection timings for the present traffic volume. The aim of this method is to provide more flexibility in signal timings relative to prior works (*9, 10*) while still minimizing disruptions.

For the above scheduling optimization problem, the nascent technology of communication can play an important role by providing real-time streaming data on the locations and the headings of various types of vehicles (*15*). With the real-time data available, an NEPV's arrival time at an intersection can be predicted with a high degree of accuracy, thus providing a data point to positively influence the TSC's future timing decisions for that intersection. If the NEPV is detected with enough time for the minimum timings for queued phases to be served, an NEPV can be guaranteed to arrive on green by modifying the intersection's timing plan.

Our work builds on the above prior efforts by applying V2I-based scheduling technologies to an isolated intersection, rather than a coordinated intersection. We aim to develop temporary timing plans based on recent performance which will accommodate an NEPV in mixed traffic flow, rather than a bus priority system, thereby allowing the benefits of the system to apply to traffic flowing in the same direction.

# SYSTEM ARCHITECTURE

## The V2I Network and Controller

As illustrated by Figure 1, the system in this paper consists of an NEPV (a bus in the figure) equipped with an on-board unit (OBU), a roadside unit (RSU), and an intersection's traffic signal controller (which operates the signals at the intersection). The OBU is capable of communication over a V2I channel with the RSU, and the RSU communicates with the signal controller using a wired Ethernet connection.

The NEPV scheduling algorithm can operate from a variety of locations. It can execute on the RSU or the controller; or it could execute on the OBU or a backend server, provided the results are relayed properly by relevant communications, be it V2I, Ethernet, or otherwise. In our system, the algorithm runs at the RSU.

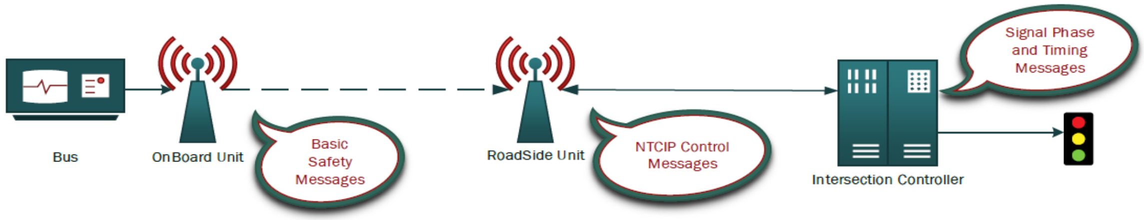


**FIGURE 1 System architecture diagram**

## TSC Command and Control

The National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) is a collection of industry standards which provide methods for TSC command and control. NTCIP uses messages in the Simple Network Management Protocol (SNMP) format (*14*). Given that our scheduling algorithm runs on the RSU, the RSU uses NTCIP to directly communicate with the controller via these SNMP messages. The messages include reading and writing phase maxima and minima, recall flags, sequences, and the controller time.

## Vehicle-to-infrastructure Communication

The transmission of an NEPV's real-time location and telemetry through V2I communication is necessary to predict the vehicle arrival that should be privileged in scheduling the dynamic priority request. The IEEE WAVE standard suites have specified the Dedicated Short-Range Communication (DSRC) 802.11p protocol, capable of providing data transfer such as basic safety messages (BSMs) via V2I communication with negligible delay (*17*).

BSM's are standardized by the SAE in SAE J2735 (*18*). Per that standard, BSM's are broadcast from a vehicle's OBU 10 times per second. The messages include the vehicle's speed, headway, acceleration, etc. These data, along with the vehicle's location, can be used to predict the arrival time of the NEPV, as well as its target phase.

For the purposes of testing the scheduling algorithm, the simulated NEPV provided its arrival time, which was predetermined by the simulation parameters to be exactly five minutes after the vehicle establishes contact with the system; in practice, this length of advanced communication is not guaranteed. However, a minimum advance time threshold can be calculated as a function of guaranteed phase minima, as discussed in the Plan Modification section. The testing of this algorithm presumes that communication can be established prior to exceeding this minimum threshold.

The NTCIP and J2735 standards (*16, 18*) also define a framework for priority requests and responses by advanced traffic controllers. This framework includes scenarios for priority requests from request generators (i.e. an NEPV) which are handled by request servers. While this study does not implement the full standard, the facets necessary for implementing the proposed functionality closely mirrored those in the standard, namely a priority request generator and server integrated into the NEPV's onboard equipment and roadside equipment, respectively.

### Signal Phase and Timing

Also described in the SAE J2735 standard (*18*) are signal phase and timing (SPaT) messages, which report the status of each phase (i.e. which direction is permitted to cross the intersection, also known as a movement state) of the traffic signals, as determined by the intersection controller. The scheduling algorithm monitors the length of the controller's phases by listening to the SPaT messages it broadcasts; this is critical to the algorithm's successful operation while the controller operates in "free" mode (i.e. it is not coordinated with other intersections along a corridor and does not stringently adhere to timing plans set up for different time periods, instead responding to demand from vehicle sensors in the roadway as traffic volumes change over the course of a day). This provides a method of estimating the length of a future controller cycle and is used to model a timing plan that can be enforced temporarily, given the present traffic conditions. The amount of previous cycles monitored is dependent on implementation; in testing, the five most recent cycles were used.

The SPaT records are also logged in our simulation to evaluate the proposed algorithm. The recorded phase lengths are provided by the high-resolution data logging functionality of the Econolite ASC/3 virtual controller. This functionality provides a record of all actions taken by the controller, including all phase changes as described in the SPaT message standard, and is leveraged by the algorithm to determine the average lengths of each phase to determine the length of a phase in the future.

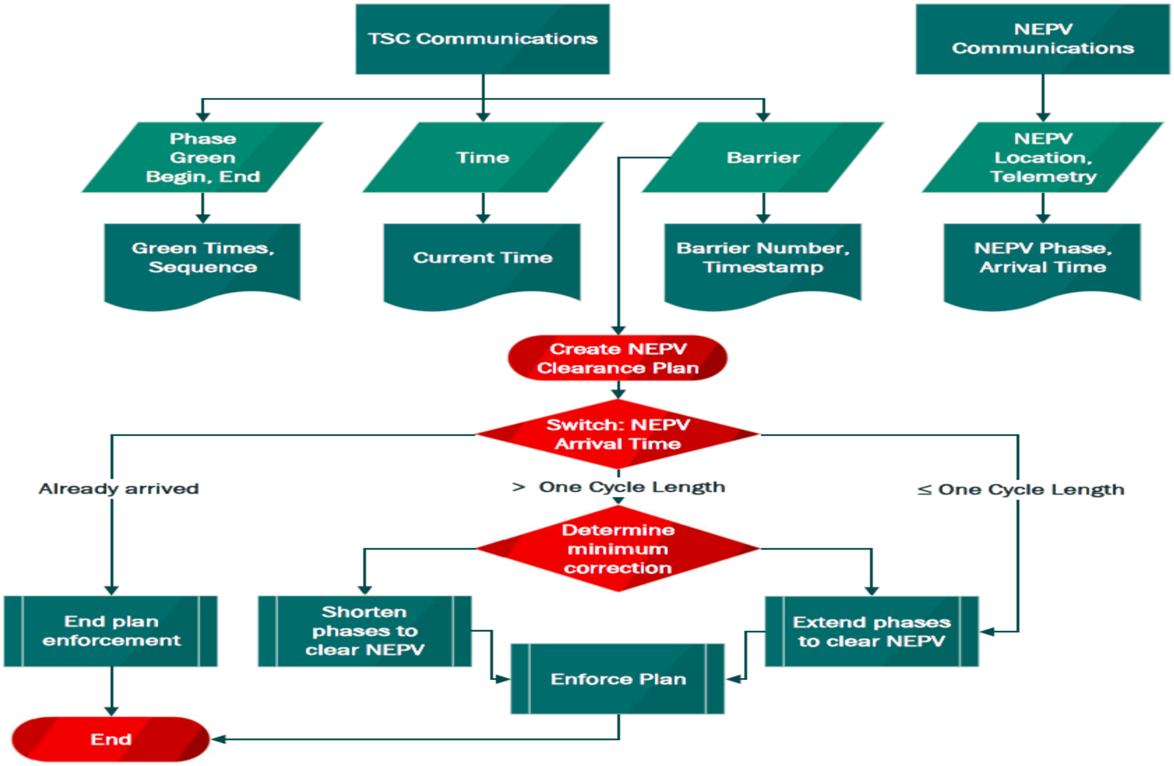


**FIGURE 2 Algorithm flowchart**

## DYNAMIC SCHEDULING ALGORITHM

In this section, we describe the general functionality of the TSC and the dynamic scheduling algorithm, including input data, clearance plan establishment, and plan modification. Figure 2 illustrates the algorithm flow.

## Algorithm Overview

Because of the behavior for a controller operating in "free" mode, prediction of a traffic signal controller's future timing is not trivial, and requires an analysis of the previous phase history to develop a model for future phase lengths. To achieve this, we monitor the SPaT data provided by the controller to keep record of previously served phase lengths. This is similar to adaptive signal control which monitors the last few cycles.

Signal timing modification done by the algorithm is initiated upon detection of a SPaT message indicating that the controller has passed a "barrier" (i.e. a point in which the intersection switches between serving the main street and cross street phases), at which point it modifies the existing timing plan for the controller to enforce strict timings based on the recent history of effectively served timings. The timing plan consists of calculated phase (i.e. green signal) lengths through which the controller will iterate, thus establishing a predictable controller cycle.

Next, the NEPV's arrival time is compared to the plan's green times allotted to the NEPV's target phase. If the NEPV is predicted to arrive outside its allotted green, the lengths of the plan's phases are adjusted accordingly in order for the NEPV to be cleared (i.e. it arrives to a green light). Finally, the plan is put into action, taking the TSC out of "free" mode on a temporary basis until such time that the NEPV has cleared the intersection. At that time, the plan is taken out of enforcement and the controller returns to "free" mode.

## Data Dependencies

The dynamic scheduling algorithm depends on the availability of the four data points discussed in this section. The phase green lengths are the input from the TSC of the current length of phase green time. To maintain a model to predict future TSC cycles, the algorithm listens via the SPaT protocol for messages indicating the beginning and ending of each phase, and maintains a record of the most recent cycles, with a particular interest in green time. Using these records, the algorithm can determine the length of an average controller cycle as well as its constituent phase lengths.

The controller time is the reference time for scheduling. The algorithm regularly polls the traffic signal controller via NTCIP to ensure clock synchronization. The arrival time predicted for an NEPV is compared against this time and a timing plan to determine when and if modifications need to be made to guarantee the NEPV arrives on green.

The barriers are time synchronization points in the TSC's timing plan to guarantee safety in the intersection, since phases of each street are generally not compatible with those of cross streets. Because these barriers provide convenient reference times at which a timing plan can be modified without interfering with the safety provided by the timing plan, these reference times can be used as a trigger to begin execution of plan modification subroutines.

Accurate GPS location and telemetry data for the NEPV being cleared are necessary to predict the arrival time for the vehicle as well as the phase to which it will be assigned. These data points are obtained via V2I communication between the RSU hardware and the NEPV's OBU hardware. As the values of these points change, the estimated arrival time can be reevaluated at each barrier to adjust a clearance plan, if necessary. An assumption is made that predictable and well-defined arrival times for NEPVs are available; while this is rather restrictive currently, the ongoing work (*5*) as well as the incipient rise of connected vehicles in the field give reason to believe this will not be as troublesome in the near future.

## Clearance Plans

To guarantee a chosen phase will be green when an NEPV arrives at an intersection, it becomes necessary to remove any uncertainty as to the length of each phase. To do this, a timing plan must be enforced which the TSC will adhere to absolutely. This stands in contrast to the default "free" operation of the TSC, in which the length of each phase is determined by the traffic volume detected by sensors at the intersection.

A timing plan is enforced upon a trigger event (i.e. a barrier SPaT message) if and only if an NEPV is predicted to arrive within the predetermined look-ahead window. This window controls the maximum amount of time the algorithm will be allowed to take the TSC out of its default “free” mode. For the purposes of testing this algorithm, the look-ahead window was defined as two times the controller’s average effective cycle length. This was chosen to ensure that a modification can be made in most circumstances if need be, and that the controller will not be taken out of “free” mode for an excessive amount of time.

If a plan has not been enforced prior to a trigger event, one is generated by calculating the average length of each phase as determined by the length records of the previous five occurrences of each phase. Once the NEPV has been cleared through the intersection, the timing plan is considered to have expired, and it is removed from enforcement, thus returning the controller to “free” mode. This allows the TSC to operate outside its standard operating mode as little as possible.

## Plan Modification

At each trigger event (i.e. barrier SPaT message), the timing plan is considered to be in force until at least the time that the NEPV arrives at the intersection. The arrival time is compared to the green times allotted to the NEPV’s target phase in the enforced timing plan. If the NEPV is predicted to arrive within a scheduled green time, no adjustment to the plan is necessary in order for the NEPV to be cleared through the intersection upon its arrival.

In the event that an NEPV is predicted to arrive outside the green times scheduled for its target phase, two cases can be considered for adjusting the timing plan to correct this: the phases of the plan can be extended so that the NEPV clears the intersection in the waning seconds of the previous scheduled green time, or the phases can be shortened so that it arrives in the first seconds of the next scheduled green time. In either case, the amount of time, if any, by which the plan must be modified, is divided across all modifiable phases to ensure no phase is asymmetrically disadvantaged.

A formula to determine by how much each phase should be shortened is shown in Equation (1), where $\Delta_s$ is the amount of time by which each phase should be shortened, $g_s$ is the difference between the phase’s current length and its guaranteed minimum green time, $O$ is the amount of time by which the full plan must be shortened, and $n$ is the number of phases in the plan before the NPEV arrives.

$$\Delta_s = \min\left\{g_s, \frac{O}{n}\right\} \tag{1}$$

Equation (2) shows the calculation of how much time should be added to each phase to guarantee the NEPV arrives to a green signal. The variables closely correspond to those of the previous equation, but no consideration of the minimum is invoked. Additionally, it is assumed that the value of $O$ cannot be larger than the timing plan’s length, so the phases will not be extended disproportionately.

$$\Delta_e = \frac{O}{n} \tag{2}$$

The option which will be chosen is determined by the time differential between the NEPV’s predicted arrival time and the termini of the previous and next green times, as illustrated in Figure 3. This figure shows which action will be taken by the algorithm based on when it is predicted to arrive (i.e. which phase in the target phase's ring, shown as the X axis) and how far in advance the vehicle's V2I communications are received (shown as the Y axis). If communication is not established far enough in advance, the algorithm will not be able to adjust the timing plan in a safe manner, so it will take no further action (shown in various shades of gray). Figure 3 omits the phases not in the same ring as the NEPV's target phase for simplicity of illustration, however these phases must also be modified accordingly.

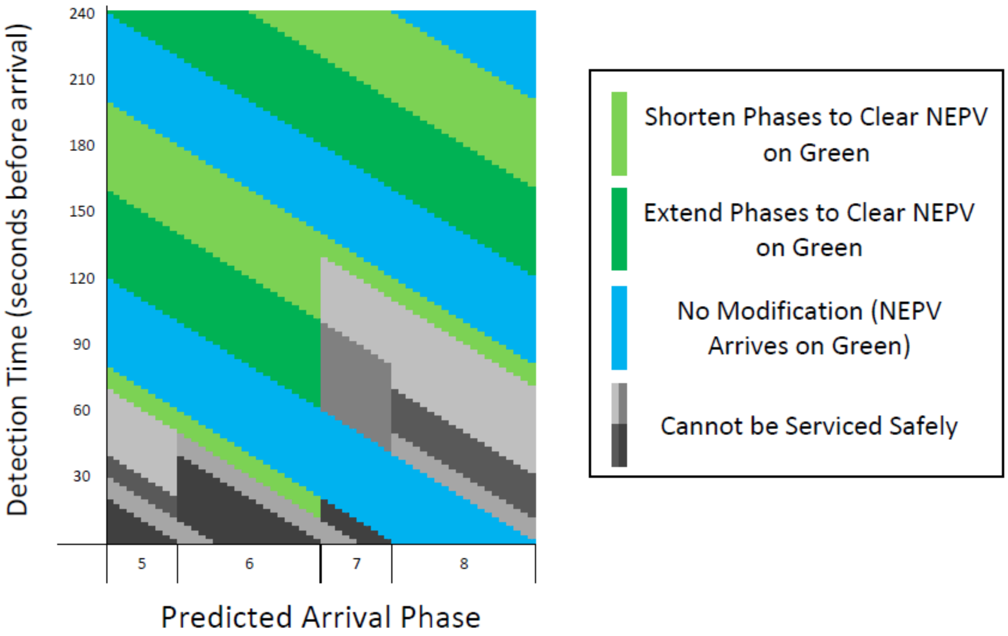
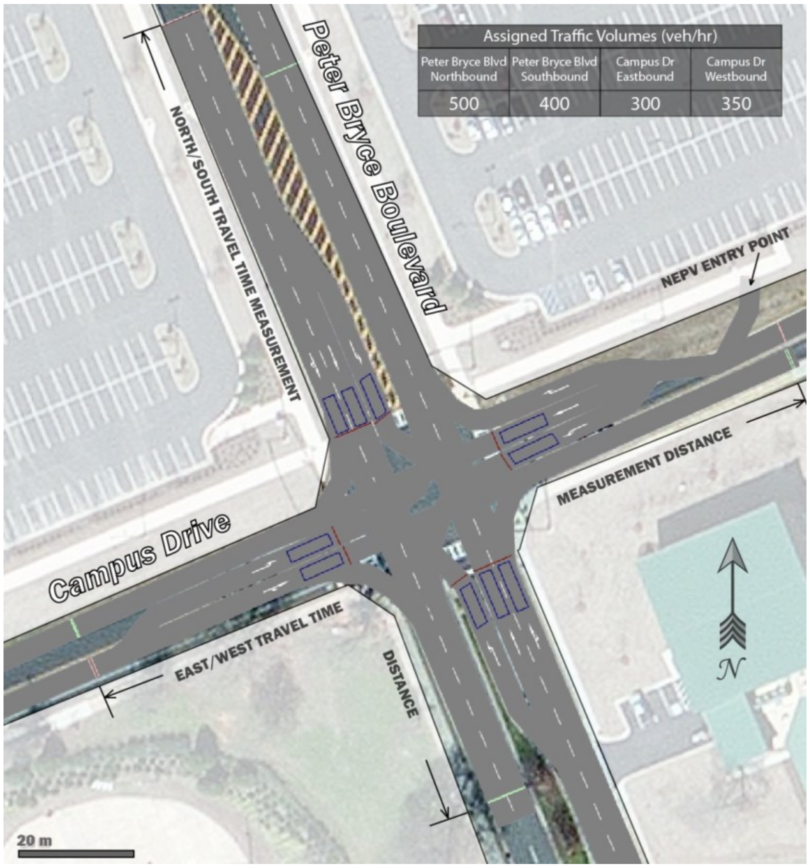


**FIGURE 3 Graph of plan modification type by detection time and predicted arrival phase when phase 8 priority is requested**

The figure shows three colored strips which correspond to the three options considered by the algorithm as a result of the NEPV's predicted arrival time. If the NEPV is predicted to arrive within its target green phase, no modification of the enforced plan is necessary (shown as a blue strip in Figure 3, wherein phase 8 is the requested phase). If this is not the case and the NEPV will arrive closer to the end of the previous green time than the start of the next green time, the phases will be extended (shown as a dark green strip); otherwise, if the NEPV will arrive closer to the start of the next phase, the phases will be shortened until the NEPV will arrive on green (shown as a light green strip). In the event that the established green time minima could not be guaranteed by the plan after shortening its phases, this option cannot be considered safe and is disregarded.

Summarily, once V2I communication has been established and the NEPV's arrival time is within the current look-ahead window (i.e. the maximum amount of time the algorithm will allow the TSC to be taken out of "free" mode), the algorithm will establish a fixed timing plan at the first barrier encountered, and will modify it to account for the NEPV's arrival time. The plan will be reevaluated at each successive barrier to make sure that the NEPV's arrival time is still within its allotted green time, until such time that the NEPV has arrived at the intersection, at which point the timing plan will be revoked.

The amount of time between when V2I communication is established and the NEPV's arrival time must exceed the minimum advance threshold when a barrier is reached in order for the algorithm to safely provide a priority clearance. This minimum threshold is a summation of the guaranteed minimum times for each phase which must be served prior to the NEPV's target phase. This minimum time can be significantly lowered by omitting or re-sequencing phases; however, these approaches were not utilized in our detailed study. Also, the effects of pedestrians in the system were not studied closely in this algorithm; however, it can be extended to incorporate these effects, provided that the minimum timings for pedestrian clearance can accommodate modification.



Assigned Traffic Volumes (veh/hr)

| Peter Bryce Blvd Northbound | Peter Bryce Blvd Southbound | Campus Dr Eastbound | Campus Dr Westbound |
|---|---|---|---|
| 500 | 400 | 300 | 350 |

**FIGURE 4 Intersection model and traffic volume table**

# SIMULATION ENVIRONMENT

The intersection studied in this paper is located at $33^\circ\,12'\,51.8''\,N,\ 87^\circ\,31'\,52.8''\,W$, at the intersection of Campus Drive East and Peter Bryce Boulevard, on the campus of The University of Alabama (UA), located in Tuscaloosa, Alabama. This location was chosen due to its frequent traversal by transit buses in UA's campus bus system, the Crimson Ride, as well as its intersection configuration that matches a standard eight-phase intersection with overlapping left-turn phases.

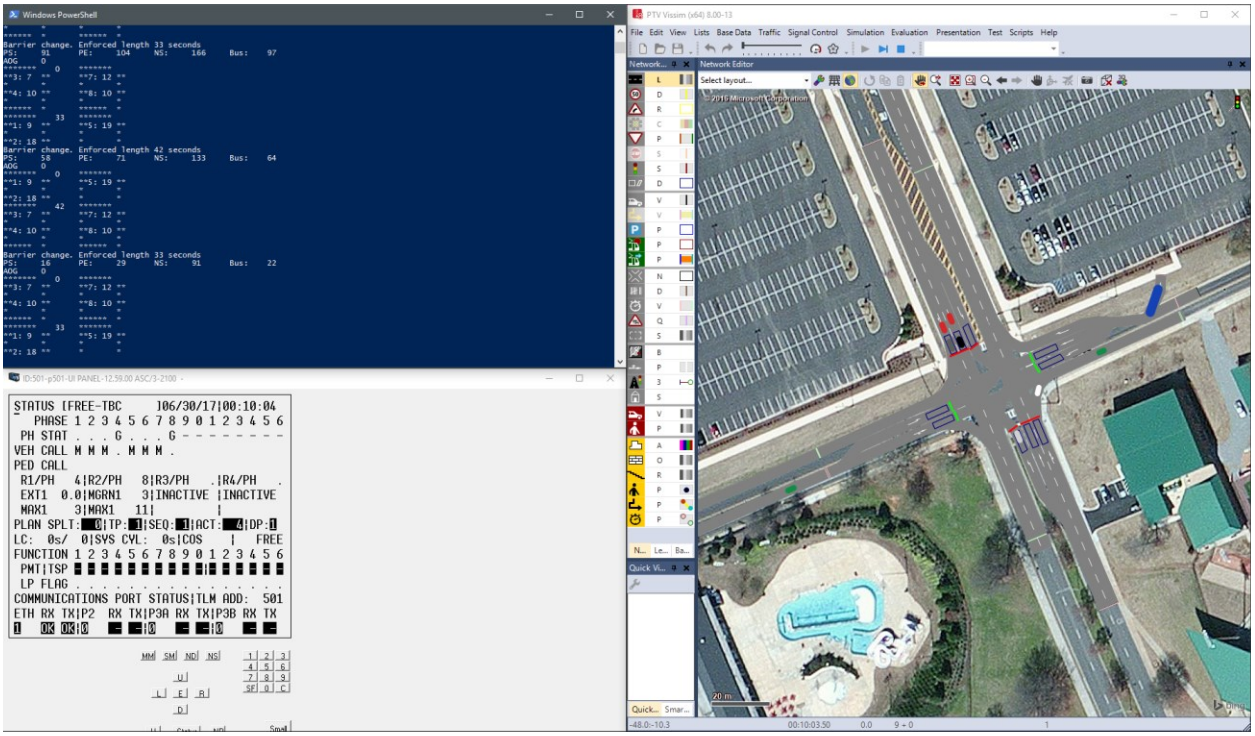
The focus intersection is located adjacent to two parking lots used by commuters, so it is likely that this intersection approaches maximum volume with regularity. Additionally, the Crimson Ride bus storage facility is located nearby, and any bus entering into service would normally traverse this intersection. This is an ideal test environment for this algorithm, as a bus being called into service at a peak traffic hour will need to cross this intersection with minimal delay to serve the campus area, and any delay encountered due to conflicting traffic will cause delay for the service's riders.

The focus intersection was modeled in the PTV VISSIM traffic simulation software, and a diagram of the intersection model can be found in Figure 4. Each street was assigned hourly traffic volumes approximating average schoolday traffic at this intersection, as detailed in the table inset in Figure 4. The VISSIM software stochastically generates vehicle traffic according to these volumes, and each vehicle traversing the intersection is registered by vehicle sensors (indicated by blue boxes in Figure 4) to provide presence data to the intersection's TSC.

The VISSIM simulation software provides a virtual traffic signal controller that emulates the functionality of an Econolite ASC/3-2100 model traffic signal controller. This controller is, by default, configured to operate in "free" mode. The controller is configured with minimum and maximum green times which may be allotted to a phase when it is in demand, as determined by the sensors in the roadway.

In order for the algorithm to respond to a non-emergency priority vehicle as intended, two details are required from the vehicle: its target phase (i.e. which phase should be green in order for the vehicle to proceed) and its predicted arrival time. Both can be determined from the data exchanged between an NEPV and an intersection using V2I communication.

To simulate these values in a controlled manner, we established an artificial bus input inside the intersection model. Indicated by an arrow in Figure 4 and shown with a bus entering in Figure 5, this vehicle input provides a method of manually inserting an NEPV (in this case, a bus) into the system while controlling the vehicle's arrival time. We were then able to provide the necessary data which the algorithm requires from V2I communication.



```
*       *       *       *
******  *       ******  *
Barrier change. Enforced length 33 seconds
PS:     91      PE:     104     NS:     166     Bus:    97
AOG     0
*******    0    *******
**3: 7  **      **7: 12 **
*       *       *       *
**4: 10 **      **8: 10 **
*       *       *       *
******  *       ******  *
*******    33   *******
**1: 9  **      **5: 19 **
*       *       *       *
**2: 18 **      *       *
Barrier change. Enforced length 42 seconds
PS:     58      PE:     71      NS:     133     Bus:    64
AOG     0
*******    0    *******
**1: 9  **      **5: 19 **
*       *       *       *
**2: 18 **      *       *
*******    42   *******
**3: 7  **      **7: 12 **
*       *       *       *
**4: 10 **      **8: 10 **
*       *       *       *
******  *       ******  *
Barrier change. Enforced length 33 seconds
PS:     16      PE:     29      NS:     91      Bus:    22
AOG     0
*******    0    *******
**3: 7  **      **7: 12 **
*       *       *       *
**4: 10 **      **8: 10 **
*       *       *       *
******  *       ******  *
*******    33   *******
**1: 9  **      **5: 19 **
*       *       *       *
**2: 18 **      *       *
```

```
STATUS [FREE-TBC      ]06/30/17|00:10:04
   PHASE 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6
 PH STAT . . . G . . . G - - - - - - - -
VEH CALL M M M . M M M .
PED CALL
 R1/PH    4|R2/PH    8|R3/PH    .|R4/PH    .
 EXT1   0.0|MGRN1    3|INACTIVE  |INACTIVE
 MAX1     3|MAX1    11|          |
PLAN SPLT:  0|TP: 1|SEQ: 1|ACT:  4|DP:1
LC:  0s/   0|SYS CYL:   0s|COS    |   FREE
FUNCTION 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6
 PMT|TSP - - - - - - - - - -|- - - - - -
 LP FLAG . . . . . . . . . . . . . . . .
COMMUNICATIONS PORT STATUS|TLM ADD:  501
ETH RX TX|P2   RX TX|P3A RX TX|P3B RX TX
1   OK OK|0    -  - |0   -  - |0   -  -
```

**FIGURE 5 Screenshot of algorithm in operation**

# SIMULATION RESULTS

Using the simulation environment described above, this algorithm was tested in ten scenarios to confirm the expected behavior under varying sets of circumstances. Each test was run as a fifteen-minute simulation, once with the accompanying algorithm and once without, with the NEPV arriving two-thirds of the way through the simulation. For each scenario (generated by varying the random seed for the simulation), the arrival time of the vehicle was varied, with 120 offset possibilities tested per scenario for a total of 2400 trials. Note that in this study, the usage of the term "offset" differs from usual usage. In this paper, the offset is used to determine the cycle starting time relative to simulation clock time rather than coordinated timing plans (the usages are related, however, as coordinated plans' offsets define cycle starts relative to clock time as well). The travel times encountered by the NEPV as well as the average travel times of all other simulated vehicles were measured in each trial.

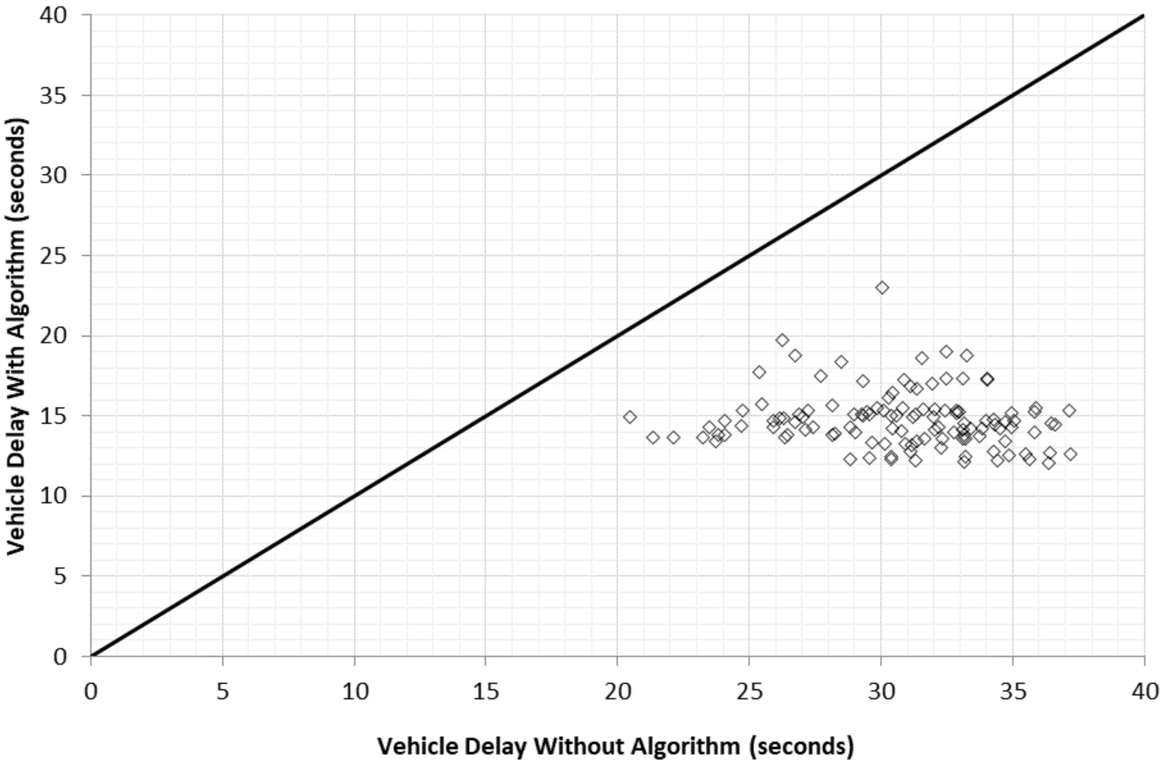


**FIGURE 6 Comparison of priority vehicle delay**

The results from the ten scenarios were averaged and compared to their respective null cases, as shown in Figure 6. This figure shows that, on average, the algorithm poses an improvement for NEPV delay, as each of the markers lies below the diagonal line where no change occurs. On a more granular level, there are individual trials recorded that include a negative improvement in the NEPV delay measurement; however, these outliers can be generally attributed to the imprecise manner of predicting the NEPV arrival time.

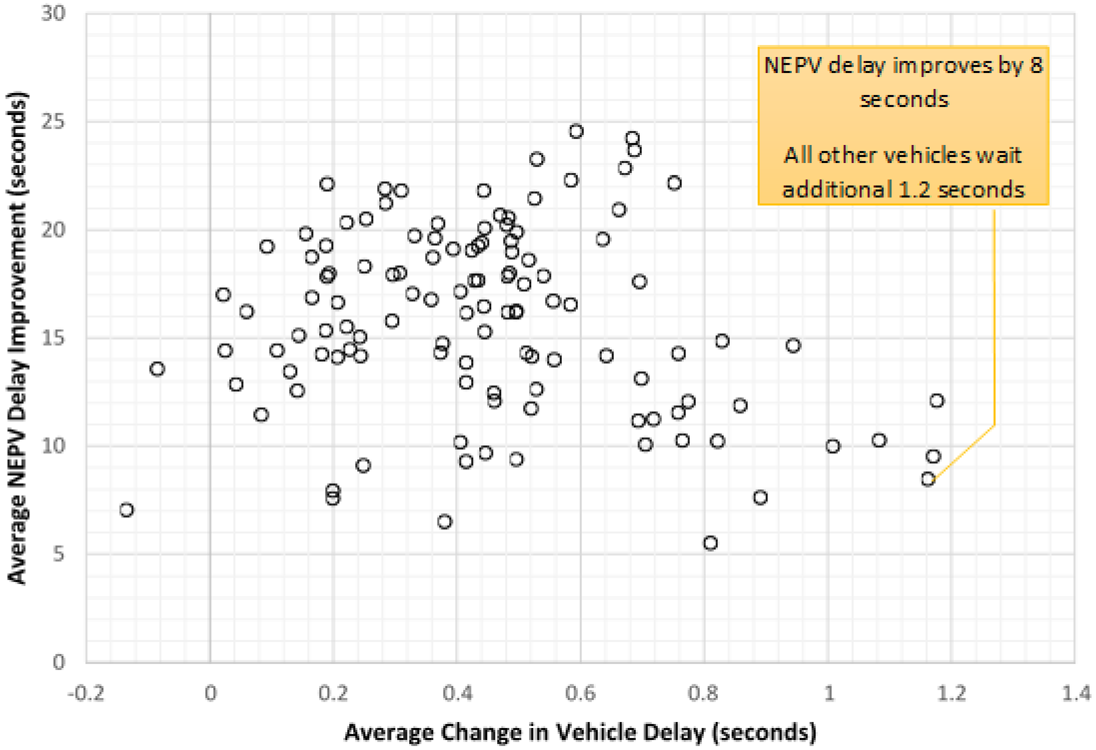
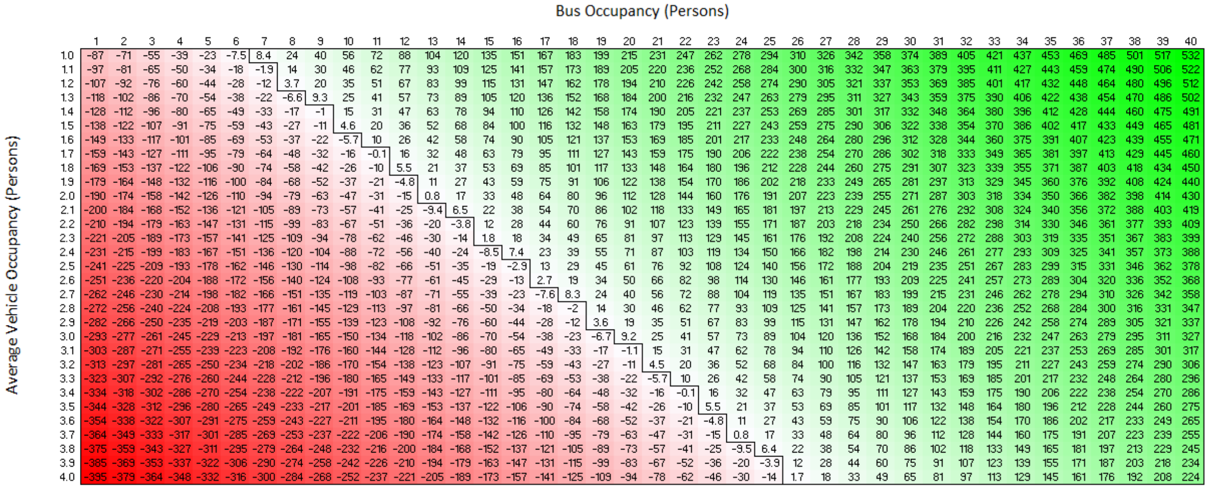


**FIGURE 7 Comparison of average priority vehicle and overall vehicle delay change**

Figure 7 shows a comparison of the average change in delay per vehicle in the system versus the average change in NEPV delay, illustrating that, while the NEPV sees a significant improvement in its delay, this comes to some small detriment of the intersection's overall delay. In one of the most extreme of cases shown in Figure 7, the NEPV delay was improved by slightly more than 8 seconds, but the average vehicle in the system incurred an additional 1.2 seconds of delay as a consequence of the algorithm. Outlier instances such as this are often due to the somewhat imprecise nature of the arrival prediction/control mechanism we employ.



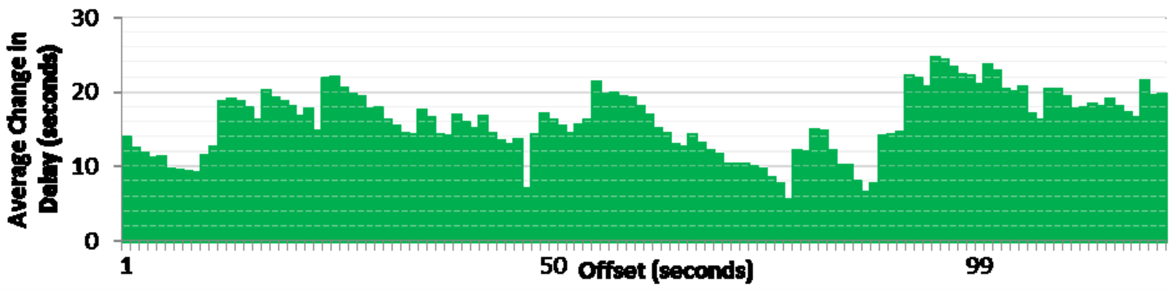
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | -87 | -71 | -55 | -39 | -23 | -7.5 | 8.4 | 24 | 40 | 56 | 72 | 88 | 104 | 120 | 135 | 151 | 167 | 183 | 199 | 215 |
| 1.1 | -97 | -81 | -65 | -50 | -34 | -18 | -1.9 | 14 | 30 | 46 | 62 | 77 | 93 | 109 | 125 | 141 | 157 | 173 | 189 | 205 |
| 1.2 | -107 | -92 | -76 | -60 | -44 | -28 | -12 | 3.7 | 20 | 35 | 51 | 67 | 83 | 99 | 115 | 131 | 147 | 162 | 178 | 194 |
| 1.3 | -118 | -102 | -86 | -70 | -54 | -38 | -22 | -6.6 | 9.3 | 25 | 41 | 57 | 73 | 89 | 105 | 120 | 136 | 152 | 168 | 184 |
| 1.4 | -128 | -112 | -96 | -80 | -65 | -49 | -33 | -17 | -1 | 15 | 31 | 47 | 63 | 78 | 94 | 110 | 126 | 142 | 158 | 174 |
| 1.5 | -138 | -122 | -107 | -91 | -75 | -59 | -43 | -27 | -11 | 4.6 | 20 | 36 | 52 | 68 | 84 | 100 | 116 | 132 | 148 | 163 |
| 1.6 | -149 | -133 | -117 | -101 | -85 | -69 | -53 | -37 | -22 | -5.7 | 10 | 26 | 42 | 58 | 74 | 90 | 105 | 121 | 137 | 153 |
| 1.7 | -159 | -143 | -127 | -111 | -95 | -79 | -64 | -48 | -32 | -16 | -0.1 | 16 | 32 | 48 | 63 | 79 | 95 | 111 | 127 | 143 |
| 1.8 | -169 | -153 | -137 | -122 | -106 | -90 | -74 | -58 | -42 | -26 | -10 | 5.5 | 21 | 37 | 53 | 69 | 85 | 101 | 117 | 133 |
| 1.9 | -179 | -164 | -148 | -132 | -116 | -100 | -84 | -68 | -52 | -37 | -21 | -4.8 | 11 | 27 | 43 | 59 | 75 | 91 | 106 | 122 |
| 2.0 | -190 | -174 | -158 | -142 | -126 | -110 | -94 | -79 | -63 | -47 | -31 | -15 | 0.8 | 17 | 33 | 48 | 64 | 80 | 96 | 112 |
| 2.1 | -200 | -184 | -168 | -152 | -136 | -121 | -105 | -89 | -73 | -57 | -41 | -25 | -9.4 | 6.5 | 22 | 38 | 54 | 70 | 86 | 102 |
| 2.2 | -210 | -194 | -179 | -163 | -147 | -131 | -115 | -99 | -83 | -67 | -51 | -36 | -20 | -3.8 | 12 | 28 | 44 | 60 | 76 | 91 |
| 2.3 | -221 | -205 | -189 | -173 | -157 | -141 | -125 | -109 | -94 | -78 | -62 | -46 | -30 | -14 | 1.8 | 18 | 34 | 49 | 65 | 81 |
| 2.4 | -231 | -215 | -199 | -183 | -167 | -151 | -136 | -120 | -104 | -88 | -72 | -56 | -40 | -24 | -8.5 | 7.4 | 23 | 39 | 55 | 71 |
| 2.5 | -241 | -225 | -209 | -193 | -178 | -162 | -146 | -130 | -114 | -98 | -82 | -66 | -51 | -35 | -19 | -2.9 | 13 | 29 | 45 | 61 |
| 2.6 | -251 | -236 | -220 | -204 | -188 | -172 | -156 | -140 | -124 | -108 | -93 | -77 | -61 | -45 | -29 | -13 | 2.7 | 19 | 34 | 50 |
| 2.7 | -262 | -246 | -230 | -214 | -198 | -182 | -166 | -151 | -135 | -119 | -103 | -87 | -71 | -55 | -39 | -23 | -7.6 | 8.3 | 24 | 40 |
| 2.8 | -272 | -256 | -240 | -224 | -208 | -193 | -177 | -161 | -145 | -129 | -113 | -97 | -81 | -66 | -50 | -34 | -18 | -2 | 14 | 30 |
| 2.9 | -282 | -266 | -250 | -235 | -219 | -203 | -187 | -171 | -155 | -139 | -123 | -108 | -92 | -76 | -60 | -44 | -28 | -12 | 3.6 | 19 |
| 3.0 | -293 | -277 | -261 | -245 | -229 | -213 | -197 | -181 | -165 | -150 | -134 | -118 | -102 | -86 | -70 | -54 | -38 | -23 | -6.7 | 9.2 |
| 3.1 | -303 | -287 | -271 | -255 | -239 | -223 | -208 | -192 | -176 | -160 | -144 | -128 | -112 | -96 | -80 | -65 | -49 | -33 | -17 | -1.1 |
| 3.2 | -313 | -297 | -281 | -265 | -250 | -234 | -218 | -202 | -186 | -170 | -154 | -138 | -123 | -107 | -91 | -75 | -59 | -43 | -27 | -11 |
| 3.3 | -323 | -307 | -292 | -276 | -260 | -244 | -228 | -212 | -196 | -180 | -165 | -149 | -133 | -117 | -101 | -85 | -69 | -53 | -38 | -22 |
| 3.4 | -334 | -318 | -302 | -286 | -270 | -254 | -238 | -222 | -207 | -191 | -175 | -159 | -143 | -127 | -111 | -95 | -80 | -64 | -48 | -32 |
| 3.5 | -344 | -328 | -312 | -296 | -280 | -265 | -249 | -233 | -217 | -201 | -185 | -169 | -153 | -137 | -122 | -106 | -90 | -74 | -58 | -42 |
| 3.6 | -354 | -338 | -322 | -307 | -291 | -275 | -259 | -243 | -227 | -211 | -195 | -180 | -164 | -148 | -132 | -116 | -100 | -84 | -68 | -52 |
| 3.7 | -364 | -349 | -333 | -317 | -301 | -285 | -269 | -253 | -237 | -222 | -206 | -190 | -174 | -158 | -142 | -126 | -110 | -95 | -79 | -63 |
| 3.8 | -375 | -359 | -343 | -327 | -311 | -295 | -279 | -264 | -248 | -232 | -216 | -200 | -184 | -168 | -152 | -137 | -121 | -105 | -89 | -73 |
| 3.9 | -385 | -369 | -353 | -337 | -322 | -306 | -290 | -274 | -258 | -242 | -226 | -210 | -194 | -179 | -163 | -147 | -131 | -115 | -99 | -83 |
| 4.0 | -395 | -379 | -364 | -348 | -332 | -316 | -300 | -284 | -268 | -252 | -237 | -221 | -205 | -189 | -173 | -157 | -141 | -125 | -109 | -94 |

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 231 | 247 | 262 | 278 | 294 | 310 | 326 | 342 | 358 | 374 | 389 | 405 | 421 | 437 | 453 | 469 | 485 | 501 | 517 | 532 |
| 1.1 | 220 | 236 | 252 | 268 | 284 | 300 | 316 | 332 | 347 | 363 | 379 | 395 | 411 | 427 | 443 | 459 | 474 | 490 | 506 | 522 |
| 1.2 | 210 | 226 | 242 | 258 | 274 | 290 | 305 | 321 | 337 | 353 | 369 | 385 | 401 | 417 | 432 | 448 | 464 | 480 | 496 | 512 |
| 1.3 | 200 | 216 | 232 | 247 | 263 | 279 | 295 | 311 | 327 | 343 | 359 | 375 | 390 | 406 | 422 | 438 | 454 | 470 | 486 | 502 |
| 1.4 | 190 | 205 | 221 | 237 | 253 | 269 | 285 | 301 | 317 | 332 | 348 | 364 | 380 | 396 | 412 | 428 | 444 | 460 | 475 | 491 |
| 1.5 | 179 | 195 | 211 | 227 | 243 | 259 | 275 | 290 | 306 | 322 | 338 | 354 | 370 | 386 | 402 | 417 | 433 | 449 | 465 | 481 |
| 1.6 | 169 | 185 | 201 | 217 | 233 | 248 | 264 | 280 | 296 | 312 | 328 | 344 | 360 | 375 | 391 | 407 | 423 | 439 | 455 | 471 |
| 1.7 | 159 | 175 | 190 | 206 | 222 | 238 | 254 | 270 | 286 | 302 | 318 | 333 | 349 | 365 | 381 | 397 | 413 | 429 | 445 | 460 |
| 1.8 | 148 | 164 | 180 | 196 | 212 | 228 | 244 | 260 | 275 | 291 | 307 | 323 | 339 | 355 | 371 | 387 | 403 | 418 | 434 | 450 |
| 1.9 | 138 | 154 | 170 | 186 | 202 | 218 | 233 | 249 | 265 | 281 | 297 | 313 | 329 | 345 | 360 | 376 | 392 | 408 | 424 | 440 |
| 2.0 | 128 | 144 | 160 | 176 | 191 | 207 | 223 | 239 | 255 | 271 | 287 | 303 | 318 | 334 | 350 | 366 | 382 | 398 | 414 | 430 |
| 2.1 | 118 | 133 | 149 | 165 | 181 | 197 | 213 | 229 | 245 | 261 | 276 | 292 | 308 | 324 | 340 | 356 | 372 | 388 | 403 | 419 |
| 2.2 | 107 | 123 | 139 | 155 | 171 | 187 | 203 | 218 | 234 | 250 | 266 | 282 | 298 | 314 | 330 | 346 | 361 | 377 | 393 | 409 |
| 2.3 | 97 | 113 | 129 | 145 | 161 | 176 | 192 | 208 | 224 | 240 | 256 | 272 | 288 | 303 | 319 | 335 | 351 | 367 | 383 | 399 |
| 2.4 | 87 | 103 | 119 | 134 | 150 | 166 | 182 | 198 | 214 | 230 | 246 | 261 | 277 | 293 | 309 | 325 | 341 | 357 | 373 | 388 |
| 2.5 | 76 | 92 | 108 | 124 | 140 | 156 | 172 | 188 | 204 | 219 | 235 | 251 | 267 | 283 | 299 | 315 | 331 | 346 | 362 | 378 |
| 2.6 | 66 | 82 | 98 | 114 | 130 | 146 | 161 | 177 | 193 | 209 | 225 | 241 | 257 | 273 | 289 | 304 | 320 | 336 | 352 | 368 |
| 2.7 | 56 | 72 | 88 | 104 | 119 | 135 | 151 | 167 | 183 | 199 | 215 | 231 | 246 | 262 | 278 | 294 | 310 | 326 | 342 | 358 |
| 2.8 | 46 | 62 | 77 | 93 | 109 | 125 | 141 | 157 | 173 | 189 | 204 | 220 | 236 | 252 | 268 | 284 | 300 | 316 | 331 | 347 |
| 2.9 | 35 | 51 | 67 | 83 | 99 | 115 | 131 | 147 | 162 | 178 | 194 | 210 | 226 | 242 | 258 | 274 | 289 | 305 | 321 | 337 |
| 3.0 | 25 | 41 | 57 | 73 | 89 | 104 | 120 | 136 | 152 | 168 | 184 | 200 | 216 | 232 | 247 | 263 | 279 | 295 | 311 | 327 |
| 3.1 | 15 | 31 | 47 | 62 | 78 | 94 | 110 | 126 | 142 | 158 | 174 | 189 | 205 | 221 | 237 | 253 | 269 | 285 | 301 | 317 |
| 3.2 | 4.5 | 20 | 36 | 52 | 68 | 84 | 100 | 116 | 132 | 147 | 163 | 179 | 195 | 211 | 227 | 243 | 259 | 274 | 290 | 306 |
| 3.3 | -5.7 | 10 | 26 | 42 | 58 | 74 | 90 | 105 | 121 | 137 | 153 | 169 | 185 | 201 | 217 | 232 | 248 | 264 | 280 | 296 |
| 3.4 | -16 | -0.1 | 16 | 32 | 47 | 63 | 79 | 95 | 111 | 127 | 143 | 159 | 175 | 190 | 206 | 222 | 238 | 254 | 270 | 286 |
| 3.5 | -26 | -10 | 5.5 | 21 | 37 | 53 | 69 | 85 | 101 | 117 | 132 | 148 | 164 | 180 | 196 | 212 | 228 | 244 | 260 | 275 |
| 3.6 | -37 | -21 | -4.8 | 11 | 27 | 43 | 59 | 75 | 90 | 106 | 122 | 138 | 154 | 170 | 186 | 202 | 217 | 233 | 249 | 265 |
| 3.7 | -47 | -31 | -15 | 0.8 | 17 | 33 | 48 | 64 | 80 | 96 | 112 | 128 | 144 | 160 | 175 | 191 | 207 | 223 | 239 | 255 |
| 3.8 | -57 | -41 | -25 | -9.5 | 6.4 | 22 | 38 | 54 | 70 | 86 | 102 | 118 | 133 | 149 | 165 | 181 | 197 | 213 | 229 | 245 |
| 3.9 | -67 | -52 | -36 | -20 | -3.9 | 12 | 28 | 44 | 60 | 75 | 91 | 107 | 123 | 139 | 155 | 171 | 187 | 203 | 218 | 234 |
| 4.0 | -78 | -62 | -46 | -30 | -14 | 1.7 | 18 | 33 | 49 | 65 | 81 | 97 | 113 | 129 | 145 | 161 | 176 | 192 | 208 | 224 |

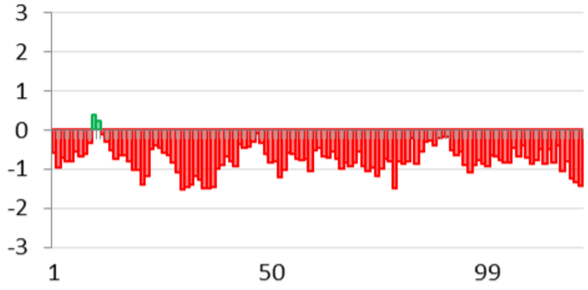
**FIGURE 8 Visualization of overall passenger delay as a function of bus and average vehicle occupancy**

One benefit of V2I communication is its ability to broadcast not just telemetry but additional information as well, such as vehicle occupancy. Figure 8 illustrates the viability of the algorithm for the test scenario based on average vehicle occupancy and average NEPV occupancy. If the NEPV is a bus with high occupancy approaches the test scenario intersection, and average vehicle occupancy is low, the algorithm effectively reduces passenger delay at the intersection, given an average of 0.4 added seconds of delay for vehicles, 16 seconds of improvement for the bus, and the vehicle volumes from Figure 4. By contrast, when bus ridership is low and vehicle occupancy is high (to the right of the solid diagonal line), the algorithm increases passenger delay. By extending this algorithm to account for these values, the algorithm can become more prudent in selecting when and how to alter the TSC's timing plans.

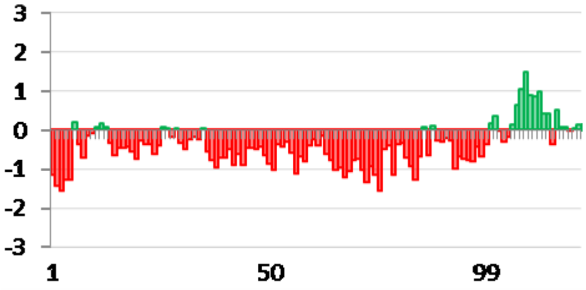
Finally, the change in average NEPV delay for each offset is shown in Figure 9a, and each individual phase's average vehicle delay is shown in Figure 9b-i. Figure 9a shows that the NEPV delay improvement ranges, on average, from about five seconds' improvement up to 25 seconds. The individual phases generally see up to a three second change in their average vehicle delay, with significantly better returns for the phases with which the NEPV's target is compatible, i.e. phases 3 and 4 which are compatible with phase 8 (the NEPV target).



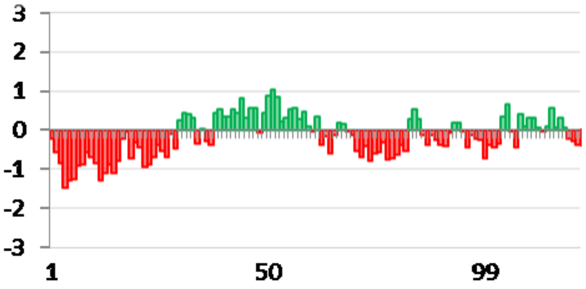
a) NEPV



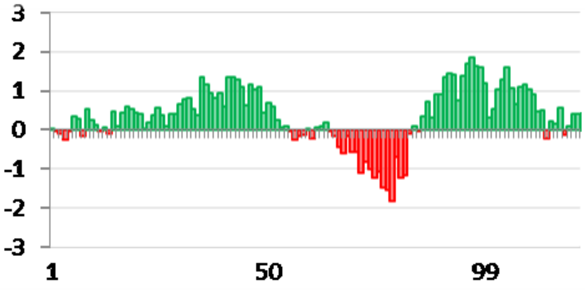
b) Phase 1



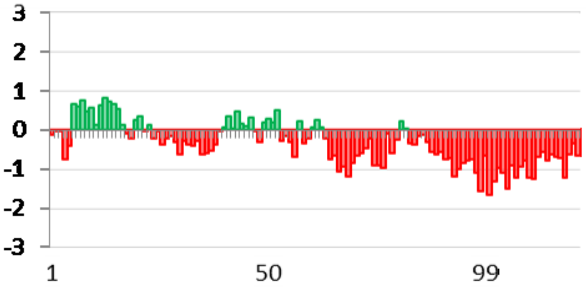
c) Phase 2



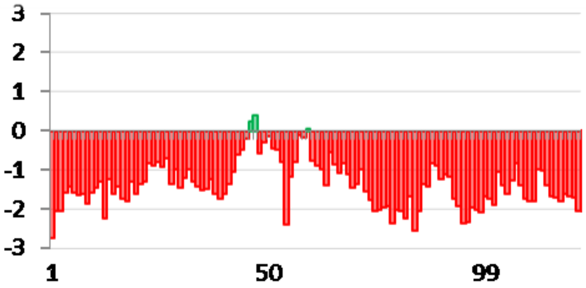
d) Phase 3



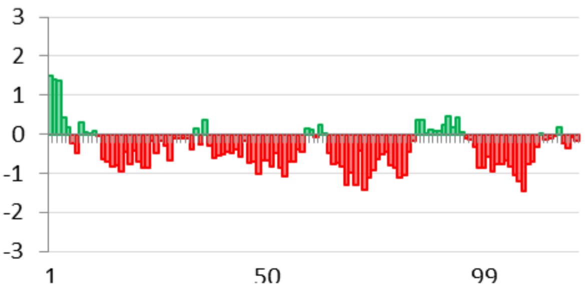
e) Phase 4



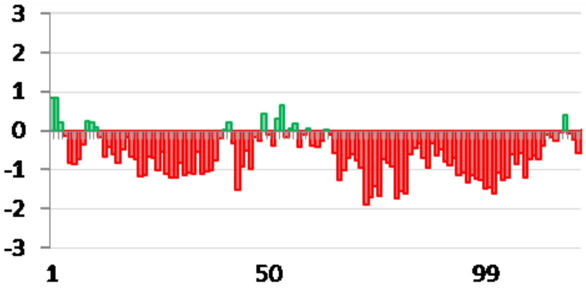
f) Phase 5



g) Phase 6



h) Phase 7



i) Phase 8

**FIGURE 9 Change in average delay for (a) priority vehicle, (b-i) phase 1-8 traffic**

# CONCLUDING REMARKS

The system we describe herein contains a functional system for using a V2I communications architecture to influence a traffic signal controller's operation to improve delay for a priority vehicle. By developing a model for recent intersection service behavior, adjusting the model in a minimally invasive manner to accommodate a priority vehicle to create a calculated timing plan, and implementing the timing plan on the controller, we established and tested an algorithm that can dramatically improve the delay encountered by a priority vehicle at an intersection without causing significant adverse consequences for other traffic.

- We developed an algorithm that monitors an actuated intersection's recent behavior, models future behavior in kind to create a potential timing plan, and adjusts the plan based on a priority vehicle's predicted arrival time.
- We developed an architecture that provides this algorithm with communication interfaces for a TSC and an RSU to provide the information on which the algorithm depends, and for command and control of the TSC to reflect the algorithm's results.
- We tested the algorithm and software architecture in simulation over 2,400 trials whose results indicate that the algorithm provides significant reduction in priority vehicle delay with minimal adverse consequences for other traffic.
- We examined the efficacy of implementing this architecture and algorithm by using varying vehicle occupancies to determine overall passenger delay. V2I communications makes it possible to share occupancy and other information for decision-making in algorithm implementation to minimize total *traveler* delay as opposed to traditional *vehicle* delay.

This system makes a series of assumptions in order to achieve its results, namely that accurate arrival time predictions are available, that pedestrians are not present at this intersection, and that the implementing intersection is isolated and not coordinated with any other signals. Moving forward, additional studies will aim to relax these assumptions to explore more market-ready implementations of this system. Additionally, more research is needed in the role that actuation can play in determining phase adjustments.

This project reflects the rapidly changing environment in traffic control communications, which will soon dramatically alter the way vehicles traverse the world's road system. By using V2I-based detection in controllers, better coordination systems will be developed that service intersections in a manner better suited to the present traffic conditions. V2I also promises to make the traditional traffic signal obsolete as vehicles begin to communicate and coordinate with each other to avoid collisions, saving time as well as improving safety for passengers.

# ACKNOWLEDGEMENTS

This work was made possible through funding from the National Science Foundation award #1541462.

# AUTHOR CONTRIBUTIONS

The authors confirm contributions to the paper as follows: study conception and design: A. Hainen, W. Alexander, X. Hong; data collection: W. Alexander, A. Hainen; analysis and interpretation of results: W. Alexander, A. Hainen, X. Hong; draft manuscript preparation: W. Alexander, X. Hong, A. Hainen. All authors reviewed the results and approved the final version of the manuscript.

# REFERENCES

1. Al-Khateeb, K. A., Johari, J. A., & Al-Khateeb, W. F. (2008). Dynamic Traffic Light Sequence Algorithm Using RFID. *Journal of Computer Science*, 517-524. doi:10.3844/jcssp.2008.517.524

2. Lou, Y., Li, P., & Hong, X. (2016). A Distributed Framework for Network-Wide Traffic Monitoring and Platoon Information Aggregation Using V2V Communications. *Transportation Research, Part C: Emerging Technologies*, 356-374. doi:10.1016/j.trc.2016.06.003
3. Qin, X., & Khan, A. M. (2012). Control strategies of traffic signal timing transition for emergency. *Transportation Research Part C: Emerging Technologies*, 1-27. doi:10.1016/j.trc.2012.04.004
4. Milanes, V., Villagra, J., Godoy, J., Simo, J., Perez, J., & Onieva, E. (2012). An Intelligent V2I-Based Traffic Management System. *IEEE Transactions on Intelligent Transportation Systems, 13*(1), 49-58. doi:10.1109/TITS.2011.2178839
5. Tan, C. W., Park, S., Liu, H., Xu, Q., & Lau, P. (2008, November 7). Prediction of Transit Vehicle Arrival Time for Signal Priority Control: Algorithm and Performance. *IEEE Transactions on Intelligent Transportation Systems, 9*(4), 688-696. doi:10.1109/TITS.2008.2006799
6. Ahmed, F., & Hawas, Y. E. (2015, August 7). An Integrated Real-Time Traffic Signal System for Transit Signal Priority, Incident Detection, and Congestion Management. *Transportation Research, Part C: Emerging Technologies, 60*, 52-76. doi:10.1016/J.TRC.2015.08.004
7. Hu, J., Park, B. B., & Parkany, A. E. (2014). Transit Signal Priority with Connected Vehicle Technology. *Transportation Researc\h Record: Journal of the Transportation Research Board, 2418*, 20-29. doi:10.3141/2418-03
8. Balke, K. N., Dudek, C. L., & Urbanik II, T. (2000). Development and Evaluation of Intelligent Bus Priority Concept. *Transportation Research Record: Journal of the Transportation Research Board, 1727*, 12-19. doi:10.3141/1727-02
9. Ma, W., Liu, Y., & Han, B. (2013). A rule- based model for integrated operation of bus priority signal timings and traveling speed. Journal of Advanced Transportation, 47(3), 369-383.
10. Li, M., Yin, Y., Zhang, W. B., Zhou, K., & Nakamura, H. (2011). Modeling and implementation of adaptive transit signal priority on actuated control systems. Computer- Aided Civil and Infrastructure Engineering, 26(4), 270-284.
11. University of Arizona, University of California PATH Program, Savari Networks Inc., and Econolite. (2016). Multi-modal intelligent traffic signal system—Phase II: System development, deployment and field test.
12. Zeng, X., Zhang, Y., Balke, K. N., & Yin, K. (2014). A real-time transit signal priority control model considering stochastic bus arrival time. IEEE Transactions on Intelligent Transportation Systems, 15(4), 1657-1666.
13. Yang, B., & Monterola, C. (2016, October 4). Efficient Intersection Control for Minimally Guided Vehicles: A Self-Organized and Decentralized Approach. *Transportation Research, Part C: Emerging Technologies, 72*, 283-305. doi:10.1016/J.TRC.2016.10.004
14. Yang, K., Guler, S. I., & Menendez, M. (2016). Isolated intersection control for various levels of vehicle technology: Conventional, connected, and automated vehicles. *Transportation Research, Part C: Emerging Technologies, 72*, 109-129. doi:10.1016/j.trc.2016.08.009
15. Guériau, M., Billot, R., El Faouzi, N.-E., Monteil, J., Armetta, F., & Hassas, S. (2016). How to assess the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies. *Transportation Research, Part C: Emerging Technologies*, 266-279. doi:10.1016/j.trc.2016.01.020
16. National Electronic Manufacturers Association. (1996, December 7). *National Transportation Communications for ITS Protocol.* Washington, D.C. Retrieved from National Transportation Communications for Intelligent Transportation Systems Protocol: http://www.ntcip.org
17. IEEE Vehicular Technology Society. (2014, March 5). *IEEE Guide for Wireless Access in Vehicular Environments (WAVE) - Architecture.* doi:10.1109/IEEESTD.2014.6755433
18. Hedges, C., & Perry, F. (2008, October 07). *Overview and Use of SAE J2735 Message Sets for Commercial Vehicles.* doi:10.4271/2008-01-2650