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Development of a Control Strategy to Reduce the Start-up Delay for Autonomous Heavy Trucks

Saeideh Esmaeili
University of Windsor

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By

Saeideh Esmaeili

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Saeideh Esmaeili

APPROVED BY:

____

E. Kim
Department of Mechanical, Automotive and Materials Engineering

____

C. Lee
Department of Civil and Environmental Engineering

____

Y. H. Kim, Advisor
Department of Civil and Environmental Engineering

August 17, 2022

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ABSTRACT

Trucks generally possess a lower level of acceleration, and the start-up delay by trucks exacerbates the signalized intersections' performance. To mitigate the impact of start-up delay, this study proposes a vehicle-specific stop point and pre-start time for the signalized intersection, which will be referred to as advanced stop point and prior start time (ASP-PST) traffic control system. It utilizes vehicle-to-vehicle (V2V) communications between the signal controller and heavy trucks. The heavy truck starts from a faraway upstream point but before the green light starts. This study provides an analytical solution for the ASP-PST traffic control that allows the heavy truck will reach a targeted location and time with a targeted speed. This innovative system has the potential to improve the efficiency and throughput of intersections, including the smooth passing of heavy trucks. Further, it enables dynamic speed harmonization in trucks and passenger vehicles mixed traffic. Results reveal that the ASP-PST traffic control performs well in various network environments. It reduced the travel time (up to 50%) while creating coordinated platoons with uniformly spaced gaps in our case study network under all tested demand patterns.

DEDICATION

This thesis work is dedicated in loving memory of the 176 lives who were victims of the Flight PS752.

Also dedicated this to my husband, Moodi, who has been a source of strength, support, patience, and motivation for me throughout this entire experience. I am truly blessed to have you in my life.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
HCM	Highway Capacity Manual
PCE	Passenger Car Equivalency
CAVs	Connected and Automated Vehicles
GLOSA	The Green Light Optimal Speed Advisory
ASP- PST	Advanced Stop Point - Prior-Start Time

CHAPTER 1
INTRODUCTION

Research Motivations

Over the past several decades, the number of trucks and their proportion in traffic has increased significantly worldwide. Trucks have played a key role in road freight transport, and 70% of the goods have been transported in the U.S. and Canada [1]. However, heavy trucks would significantly decrease traffic flow efficiency due to the additional roadway space occupied by trucks and their acceleration capability, which requires a longer acceleration distance and time. The problem of inefficient traffic flow will be more significant at signalized intersections in urban streets because queues develop behind slow-moving lead trucks. An 80,000 pounds fully loaded heavy truck, which is a U.S. federal limit, would take 40 seconds from a full stop to 40 km/h (11.1 m/s) with a slowly accelerating rate of 0.28 m/s^2, and it would be around 24 seconds headway with a standard front passenger car (with a standard acceleration rate of 2.0 m/s^2) [2].

Furthermore, the existence of heavy trucks in the intersection hinders the harmonization of the speed of vehicles in the network [3]. They develop large gaps in front of them. These imbalanced speeds and gaps can lead to unnecessary stops, congestions, bottlenecks, and incidents. Besides, trucks consume significantly more fuel during stop-and-go traffic, and they are far more pollutants than passenger cars.

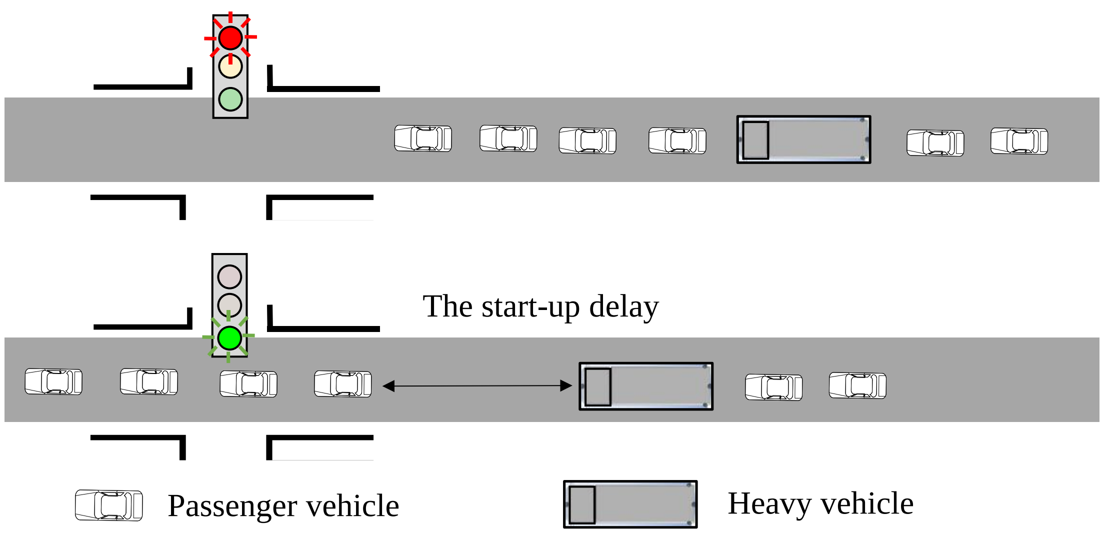


Figure 1-1 Impact of the start-up delay for a platoon formation with a mixed traffic

Figure 1-1 illustrates the impact of start-up delay for a platoon with mixed traffic. The upper figure shows seven vehicles are approaching the intersection. The truck locates fifth in the order as shown. The lower figure shows a longer headway between the front passenger vehicle and the following fifth heavy truck. While improvements in vehicle design and automation, it will be difficult to overcome the physical difference. A control strategy has to cope with various combinations of mixed vehicles in the formation of a platoon in a signalized intersection. Therefore, tackling trucks start-up delays and smooth passing is a crucial step in transportation system improvement. We shall investigate in the following section some of the consequences of this, particularly as applied to heavy vehicle mixed traffic in intersections.

Research Objectives

To bridge the aforementioned gaps, this study proposes an advanced stop point (ASP) and prior-start time (PST) traffic control system. The objectives of this study are to:

1. Propose an innovative system to diminish heavy vehicles start-up delay at intersections
2. Propose a mathematic solution for ASP-PST method
3. Develop a traffic model to simulate traffic flow at intersection networks to minimize travel time
4. Examine the efficiency of truck movement in mixed traffic with the proposed method

Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 provides a review of the existing literature that have been conducted to study a solution to diminish the start-up delay of the heavy vehicles. Chapter 3 will discuss the basic CAVs technologies for the system and briefly talk about the concept of ASP-PST traffic control. Chapter 4 presents the mathematical procedure to obtain analytical solutions for the optimal speed trajectory of individual vehicles. In Chapter 5, we provide the simulation environment characteristics, parameters, and various test setups. Furthermore, it implies numerical experiments to analyze the proposed ASP-PST traffic control capabilities and compares them to the traditional traffic signal. Finally, Chapter 6 explains the main findings and and the recommendations for future work.

CHAPTER 2
LITERATURE REVIEW

Advanced Traffic Signal Control

Earlier studies used traffic signal control approaches to reduce intersections loss time and optimize vehicles travel time. We can categorise CAV-based traffic signal controls into three groups: actuated traffic signals, platoon-based traffic signal control, and planning-based traffic signal control.

Actuated (adaptive) traffic signal control approaches

The actuated (adaptive) traffic signals methods, by considering the current vehicle volume, may increase or decrease the green signal. They modify the timing parameters actively to adapt to the real-time traffic states. Compared to the fixed-time signal control, the adaptive traffic signals increase the intersection capacity effectively (4). These methods, by analysing the accurate information that CAVs provide, change the length of the current phase or even add an extra phase to appropriately make adjustments to the signal. Gradinescu et al. proposed an actuated traffic signal control that estimated the traffic volume of each cycle, and then they used the Webster's formula (5) to get the optimized cycle length (6).

The platoon-based signal control approaches

Actuated traffic control is more dependent on current real-time traffic data and less on predicted traffic conditions. However, platoon-based traffic signal control depends on detailed traffic prediction. The platoon-based signal control approaches would optimize the signal timing and phases together. Platoon-base signal control attempt to schedule signal timing to traverse the intersections while minimizing the waiting at the intersections by classifying vehicles in platoons. They simulate their model on two intersections and the results showed reduction in travel time and fuel consumption compared to the traditional signal control. Pandit et al. proposed a platoon-based signal control methodology. They consider the traffic control problem as processors job scheduling problem. In their assumptions, jobs represent platoons of vehicles d all jobs have equal sizes. They feed all jobs to an online algorithm to minimize the delay at intersections. They simulated their proposed method on a single intersection and the results showed that this methodology reduced the travel time on light and medium traffic, however in heavy traffic conditions, it could not be advantageous (7). He et al. developed a platoon-based multi-modal dynamic platoon progression model to control traffic signals. They proposed a platoon identification based on vehicles' headway. Next, they optimized traffic control system according to the platoon information, signal data, and priority requests using mixed-integer linear program (MILP) algorithm. Their simulation results in VISSIM implied 8 percent delay reduction at intersection comparing to a coordinated actuated signal control method (8).

The planning-based signal control approaches

Platoon-based approaches are deficient in taking into account the inside platoon interactions and individual-level vehicles dynamics. While, the planning-based signal control methods consider each vehicle individually, which is a better representation of real-world traffic. Feng et al. proposed an optimized real-time signal control approach using CAVs data and conduct their results on environments with different penetration rate. They estimated the unequipped vehicles dynamics by doing a regional analysis on roads and then predict vehicles arrival time for a specific time step in future and then develop an optimization model to minimize delay and the length of the queue at the intersections using dynamic programming. They simulated their model in VISSIM and their results indicated upto16.33% reduction in total delay in the high penetration rate scenario compared to the actuated signal control (9).

Transit signal priority (TSP) control is also sub-section of planning-based traffic controls. These methods upon any request normally take three strategies: extending the green signal (if the current signal is green), inserting an extra green signal, and returning to the green signal (if the current signal is red). The main issues that needed to be addressed in such methods is the conflict with the priority requests. Hu et al. proposed a person-delay-based optimization method for an intelligent TSP that handles several conflicting requests at a single intersection using a binary mixed integer linear program to minimize per-person delay. Results indicated that this method compared with the traditional first-come-first-out TSP methods, reduced the bus delay by 48%. Although these strategies could reduce loss time at intersections, they are generally restricted to giving priority to only left turn movements (10).

Fright Signal Priority (FSP) methods also allocate certain priority to trucks across truck routes. These priorities give trucks enough time to pass the intersection without waiting or return to green signal if they already stopped at the intersection. Zhao et al. proposed an FSP-based approach using simulation and optimization to determine the optimal timing for the traffic signal. Their results showed 28 percent delay reduction over 3 and 20 proportion of truck traffic (11). Park et al studied the operational and environment effects of FSP using VISSIM simulation. The results implied that their methodology not only improved traffic operation but also fuel consumption (reduced by 11.8 percent) and emissions (reduced between 11.8 and 25.9 percent) reduced significantly (12). Although FSP would decrease truck delays efficiently, it may cause delays on side streets, especially in the cases with the high volume of trucks in the traffic.

Advanced driver guidance based on CAVs

Another solution to improve the intersection traffic are based on driver guidance using CAVs onboard technologies. For instance, The Green Light Optimal Speed Advisory (GLOSA) system suggests speeds for vehicles, allowing them to pass through an intersection during the green interval with minimum delay and unnecessary stops. Stevanovic et al. modeled a GLOSA method on a two-intersection network in VISSIM and evaluated their proposed method in two scenarios: predictable fixed-time signal timing and unpredictable actuated–coordinated signal timing. The results indicated that using GLOSA systems is not worthwhile in the actuated–coordinated signal timings. However, in the fixed-time signals, the more GLOSA activations leads to increasing the intersection traffic efficiency (13).

Some studies used Dynamic Speed Harmonization (DHS) and regulates the speeds of CAVs to optimise traffic flow by dynamically adjusting and coordinating vehicle speeds to prevent them from excessive stops at intersections. He et al. (2015) proposed a multi-stage DHS methodology to control vehicles trajectory at intersections optimally with consideration of queue at intersection. They introduced an optimization formulation that facilitate the optimal speed control system updates in the real-time. Although their proposed model could not reduce travel time at intersection, their model showed promising results in fuel consumption with 40% reduction comparing to no advice scenario (14). Tajalli et al. presented a DHS method in urban area. Their results showed reduction in travel time, speed variation, and number of stops at intersections. They utilized the Cell Transmission Model (CTM) as a core of their traffic flow model. Although, their approach had promising results on medium-sized urban networks, it could not be extended to large-scaled networks because of involving complex computations (15).

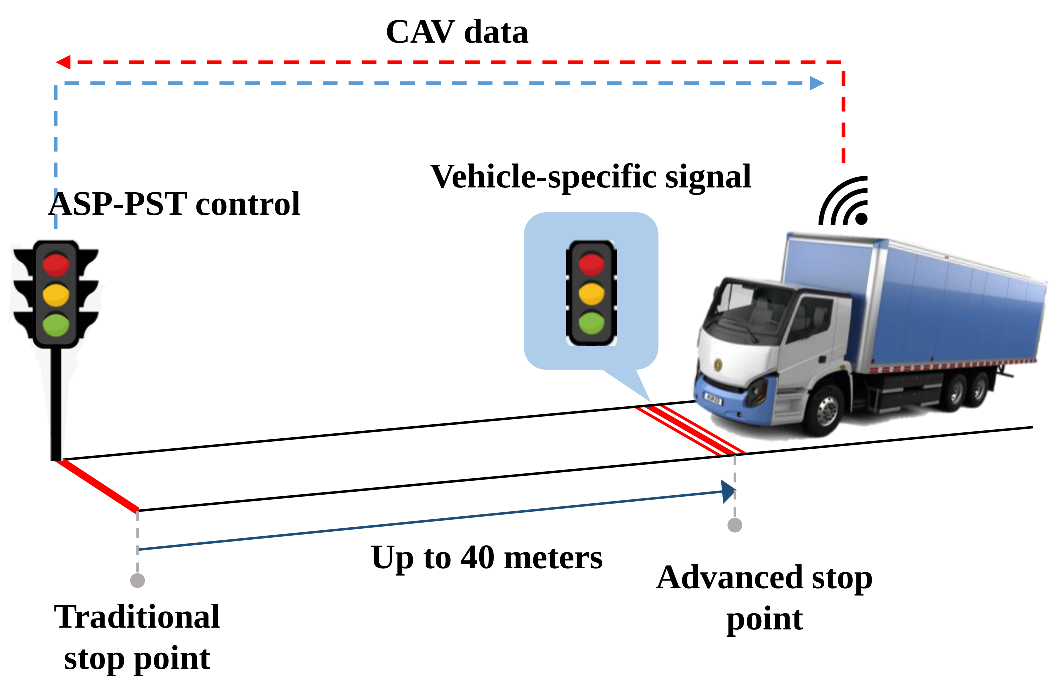
Due to the complexity and the computation cost of optimization methods, they are challenging to employ for the real-time large-scale networks comparing to other strategies. Moreover, most of the previous studies were developed without considering different vehicle types in areas with a high volume of heavy trucks; treating all vehicles the same may create problems.

CHAPTER 3

PRELIMINARY

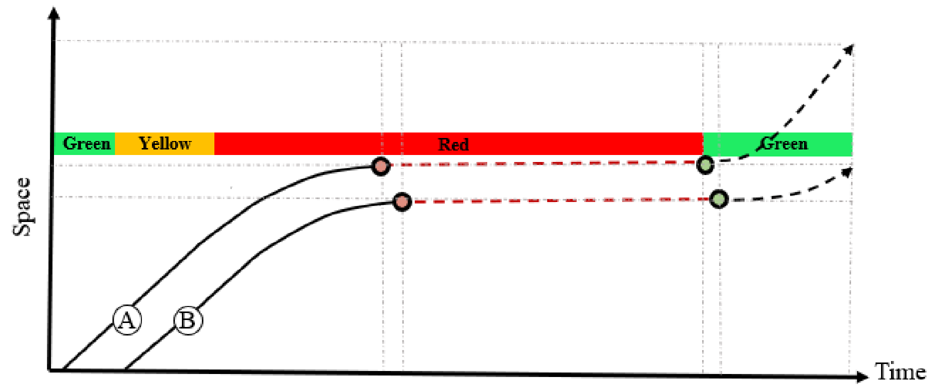
Concept of the ASP-PST

The ASP is a vehicle-specific stop point located some distance ahead of the intersection's stop line, and the PST is the time when a designated heavy truck starts to traverse from the ASP. Figure 3-1 (a) illustrates the conceptual idea of the ASP-PST control system. The proposed system leverage CAV capability to provide a vehicle-specific signal for an approaching heavy truck through communication.

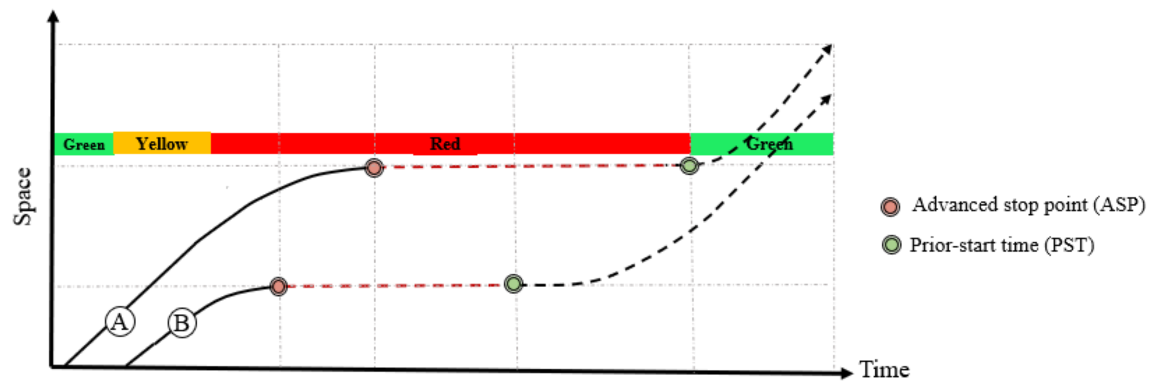


a) Conceptual illustration of the ASP-PST control

Vehicle	Acceleration rate
A (delay-free trajectory)	2.0 m/s^2 (= Standard passenger car)
B (Heavy truck trajectory)	0.5 m/s^2 (= Heavy-loaded truck)



b) Traditional system time-space diagram (no control)



c) ASP-PST traffic control system time-space diagram

Figure 3-1 ASP-PST traffic control system

Figure 3-1 (b) and (c) illustrate differences between traditional signal control (no control) and the proposed control system. The vehicle-A accounts for a delay-free trajectory with 2 m/s^2 acceleration rate, which equals to passenger car's acceleration rate, and the slowly accelerating heavy truck with 0.5 m/s^2 acceleration rate (marked as B) is represented by plotting its position as a function of time. We assume that the vehicles approach the traffic light in an ordered sequence without passing. The figure includes the state of the traffic light on the top of the figure. Two vehicles shown here initially travel at a constant speed rate and slow down when signal turns red as they approach the intersection. Figure 3-1 (b) shows that the traditional signal (no control) uses the intersection stop line. Considering the trajectory of B (heavy truck), a significant start-up loss and gap between them and the lead vehicle (A) is associated with the heavy truck. On the other hand, in Figure 3-1 (c), the proposed traffic control system uses the ASP-PST that allows the heavy truck to stop ahead of the intersection stop line (e.g., 40 meters) and start prior (e.g., 15 seconds) to the green time signal. The ASP and PST represent the decision variables. These traffic controls are formulated considering the truck's maximum acceleration capability and vehicle position in the queue.

Contributions

This system may improve the efficiency of intersections by eliminating the start-up delay. It can further make speed harmonization in urban street corridors to improve traffic operations and help to achieve platoon-based signal control. As a result, a smooth passing of intersection may reduce air pollution and fuel consumption, which is beneficial environmental-wise. Moreover, it can be adopted in signalized corridors and routes where the corridor is a vital freight route near ports, industrial areas, or distribution centers. Furthermore, it can also be applied to an uphill traffic signal where the time to accelerate from a red light is longer (*22*).

Subject Control Vehicle Determination

This section determines which vehicles will be subject to the ASP-PST control. Figure 3-2 depicts the subject vehicles in the ASP-PST traffic control system. Only some vehicles within the blue area are potential candidate vehicles. This area is for situations where the vehicle should stop or reduce the speed at the intersection. Vehicles that are not within the area will not be controlled.

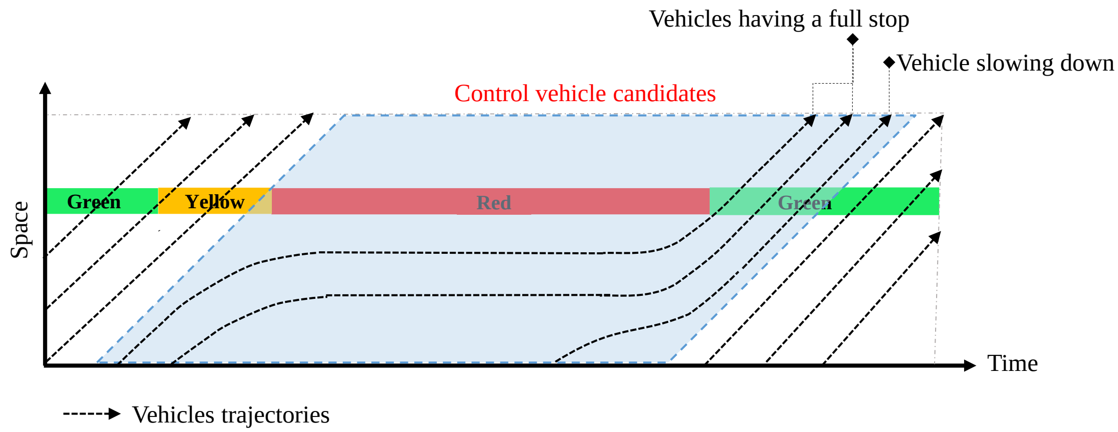


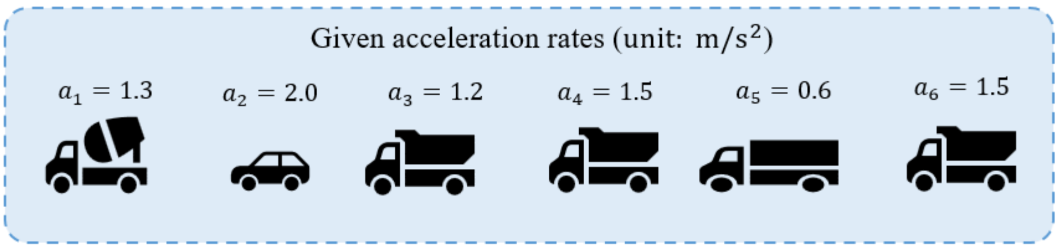
Figure 3-2 Illustration of candidate of vehicles under the ASP-PST control

The identification of subject (control) vehicles consists of two steps. First, recognition of the approaching vehicles which are projected to stop or slow down (due to the downstream vehicles stopped on red signal) at the intersection. This projection should be conducted τ seconds before the green signal phase ends. This look-ahead checking time point (τ seconds) is determined based on the time that the slowest accelerating vehicle is to be located at the ASP location. Second, among vehicles projected to stop or slow down, the subject vehicles are determined based on the acceleration capability and the approaching order to the intersection. If there is a slower vehicle in front of the subject vehicle, that slower vehicle will determine the trajectory of that subject vehicle. Therefore, there is no need to provide the ASP-PST solution for this vehicle. The system compares each vehicle's acceleration with the queue of vehicles in the front. Eq. 1 expresses the selecting condition of the subject vehicle, *i*, based on the acceleration of vehicle *i* (a_i). For the first vehicle in the queue, if it possesses lower acceleration than the standard passenger car acceleration, it will be subjected to the ASP-PST control system.

For vehicle i, if $a_i < \omega$ for *i*=1 (1)

$a_i < \text{Min}(a_k, a_{k+1}, \dots, a_{i-1})$ for *i*>1

Figure 3-3 illustrates an example where six vehicles are expected to stop with distinct acceleration rates. Their acceleration is $a_1 = 1.3ms^{-2}$, $a_2 = 2ms^{-2}$, $a_3 = 1.2ms^{-2}$, $a_4 = 1.5ms^{-2}$, $a_5 = 0.6ms^{-2}$, and $a_6 = 1.5ms^{-2}$, respectively. In this study, a standard passenger car's acceleration is considered as $2ms^{-2}$. Since the first vehicle's acceleration is lower than 2 ($a_1 < 2$), it is identified as the control vehicle. As the second vehicle's acceleration is larger than the first one, $a_2 > a_1$, the ASP-PST traffic control strategy will not be applied to the second one and it will follow its lead vehicle. For the third vehicle, by comparing a_3 with the minimum acceleration among all the vehicles ahead of vehicle 3, the third vehicle will be a subject vehicle to be controlled ($a_3 < \min(a_1, a_2)$). By comparing vehicles' acceleration through the queue, vehicles 1, 3, and 5 are subject vehicles in this case.



Condition	Checking the condition	Control vehicle
For vehicle 1, if $a_1 < 2$	$1.3 < 2$	Yes
For vehicle 2, if $a_2 < \min(a_1)$	$2 > \min(1.3) = 1.3$	No
For vehicle 3, if $a_3 < \min(a_1, a_2)$	$1.2 < \min(1.3, 2) = 1.3$	Yes
For vehicle 4, if $a_4 < \min(a_1, a_2, a_3)$	$1.5 > \min(1.3, 2, 1.2) = 1.2$	No
For vehicle 5, if $a_5 < \min(a_1, a_2, a_3, a_4)$	$0.6 < \min(1.3, 2, 1.2, 1.5) = 1.2$	Yes
For vehicle 6, if $a_6 < \min(a_1, a_2, a_3, a_4, a_5)$	$1.5 > \min(1.3, 2, 1.2, 1.5, 0.6) = 0.6$	No

Figure 3-3 An example of determining the subject vehicles

CHAPTER 4

METHODOLOGY

In this section, first, the logic and types of ASP-PST traffic control are described. Then mathematical formulation of the proposed control system will be discussed. It is formulated using Newton's laws of motion. All symbols used in developing the model are listed in Table 4-1.

Table 4-1 Notations

Notation	Description	Unit
	Variables for signal timing	
t_g	Timestamp when the green signal starts and assumed as 0	s
t_c	Look-head checking time (τ seconds before the green signal ends)	s
	Variables for the delay-free virtual trajectory	
$X'(t)$	Delay-free virtual position trajectory	m
$V'(t)$	Delay-free virtual speed trajectory	ms^{-1}
a'	Acceleration of delay-free (standard passenger) vehicle	ms^{-2}
t'_{opt}	Timestamp when delay-free trajectory reaches the speed limitation rate (desired speed)	s
X'_{opt}	Position of the delay-free vehicle at timestamp t'_{opt}	m
	Variables for the subject vehicle	
$X(t)$	Subject heavy truck position trajectory	m
$V(t)$	Subject heavy truck speed trajectory	ms^{-1}
a	Acceleration of subject vehicle	ms^{-2}
b	Deceleration of subject vehicle	ms^{-2}
t_d	Timestamp when the subject vehicle starts slowing down (decelerating)	s
t_a	Timestamp when the subject vehicle starts accelerating	s
t_s	Timestamp when the subject vehicle stops at the intersection	s
X_0	Position of the subject vehicle at timestamp t_c	m
X_c	Threshold position of the subject vehicle at timestamp t_c	m

Determining the Type of Control

Depending on whether the vehicle is required to stop or slow down, the type of control is determined. The first type of control (Type I) is for those vehicles that make a full stop at the intersection during the red signal. The subject vehicle enters the intersection, stops at the ASP ($X(t_a)$), and then starts traveling at the PST (t_a). The second type of control (Type II) is for those vehicles that slow down due to the downstream vehicles and start accelerating at the position ASP and the time PST. To calculate the ASP and PST of Type I and II, we apply different Newton's laws of motion. A boundary divides Type I and II controls and it is illustrated as a blue line in speed-time and space-time diagrams in Figure 4-1.

This boundary is the trajectory that the vehicle decelerates at a comfort rate of deceleration (① trajectory) and accelerates with a vehicle-specific acceleration rate (② trajectory) as soon as its speed comes to zero. Then, this trajectory is coupled with a delay-free trajectory (③ trajectory plotted as a two-line green line) at point A as shown in Figure 4-1. The delay-free trajectory is virtual and used for the benchmarking one. The delay-free trajectory is built assuming it starts traveling from the intersection stop-line point when the signal turns green with the desired acceleration rate of the passenger vehicle to get to the speed limitation of the road or desired speed (V_{lmt}). It is noted that the delay-free trajectory can be used to determine the desired destination coordinates for the subject vehicle (Point A) and the start-up point for each subject vehicle can be calculated accordingly to pass the intersection without start-up loss.

Those vehicles arriving before the boundary (yellow lines) will be controlled as Type I and those vehicles arriving later and only slowing down (pink lines) will be controlled as Type II.

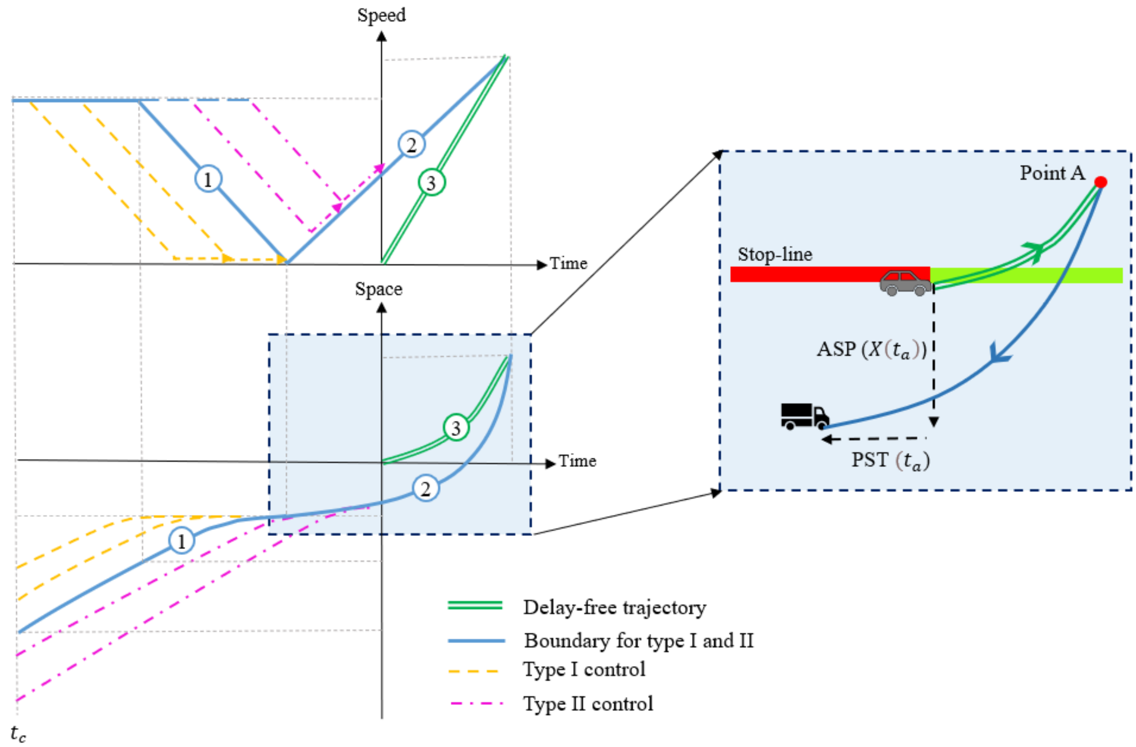


Figure 4-1 Boundary for the ASP-PST control type

The following steps (1 to 6) are used to calculate the boundary of the control heavy truck for types I and II. Suppose the vehicle is approaching with constant speed (V_0), then decelerates at the constant rate (b) to stop in some location prior to the intersection stop-line for a specific period. If the subject vehicle at the look-ahead checking time (t_c) is prior to X_c, the control type is considered as Type I and otherwise it will be Type II. The following steps are required to take in order to compute X_c for each subject vehicle. Each step is illustrated in Figure 4-2 with an associated number (e.g. ①).

Step 1: The virtual vehicle trajectory can be drawn by starting from the intersection stop-line point (x = 0) when signal turns green ($t = t_g$= 0). It will reach the speed limitation of the road or desired speed (V_{lmt}) with the desired acceleration rate (a'). This point stamp (t'_{opt}, X'_{opt}) is calculated as follows:

$$t'_{opt} = \frac{V_{lmt}}{a'} \tag{2}$$

$$X'_{opt} = \frac{1}{2} a^p \cdot (t'_{opt})^2 \tag{3}$$

Step 2: t_a is the timestamp that the subject vehicle instantly stops and starts traveling with its acceleration rate (a) and comes to the X'_{opt} at the time t'_{opt}. t_a is calculated using Eq. (4):

$$t_a = V_{lmt}\left(\frac{1}{a'} - \frac{1}{a}\right) \tag{4}$$

Step 3: t_d is the timestamp that the subject truck should start decelerating to stop at the intersection. Knowing t_a and going backward through the speed-time plot, t_d can be calculated as:

$$t_d = V_{lmt}\left(\frac{1}{a\prime} - \frac{1}{a}\right) + \frac{V_0}{b} \tag{5}$$

Step 4: By computing X'_{opt} in the subject vehicle trajectory between the time interval t_a and t'_{opt} in the space-time diagram, we can write the following equation:

$$X'_{opt} = X(t_a) + \frac{1}{2}a\left(t'_{opt} - t_a\right)^2 \tag{6}$$

By setting Eq. (3) and Eq. (6) equal, Eq. 7 is obtained.

$$\frac{1}{2}a'\left(t'_{opt}\right)^2 = X(t_a) + \frac{1}{2}a\left(t'_{opt} - t_a\right)^2 \tag{7}$$

By inputting t'_{opt} from Eq. (2) and t_a from Eq. (4), $X(t_a)$ would be formulated as:

$$X(t_a) = \frac{(V_{lmt})^2}{2}\left(\frac{1}{a'} - \frac{1}{a}\right) \tag{8}$$

Step 5: By considering the subject control vehicle trajectory between the time interval t_a and t_d, Eq. (6) can be written as:

$$X(t_d) = X(t_a) + \frac{1}{2}b(t_a - t_d)^2 \tag{9}$$

Replacing $X(t_a)$, t_a, and t_d using Eq. (8), Eq. (4), and Eq. (5) respectively, we have:

$$X(t_d) = \frac{(V_{lmt})^2}{2}\left(\frac{1}{a'} - \frac{1}{a}\right) + \frac{{V_0}^2}{2b} \tag{10}$$

Step 6: Now, the relation between $X(t_d)$ and X_c simply can be derived from the space-time trajectory in the t_c to t_d time interval. Thus:

$$X_c = X(t_d) - V_0(t_a - t_c) \tag{11}$$

The final equation for X_c by substituting $X(t_d)$from Eq. (10) and t_a from Eq. (4) can be derived as:

$$X_c = V_{lmt}\left(\frac{V_{lmt}}{2} - V_0\right)\left(\frac{1}{a'} - \frac{1}{a}\right) - \frac{(V_0)^2}{2b} + V_0 t_c \tag{12}$$

At this point, Eq. (12) should be determined for each control vehicle to compute the threshold position by which the control type would be provided. In the following, the mathematical procedure to compute the start-up point in both control types is discussed.

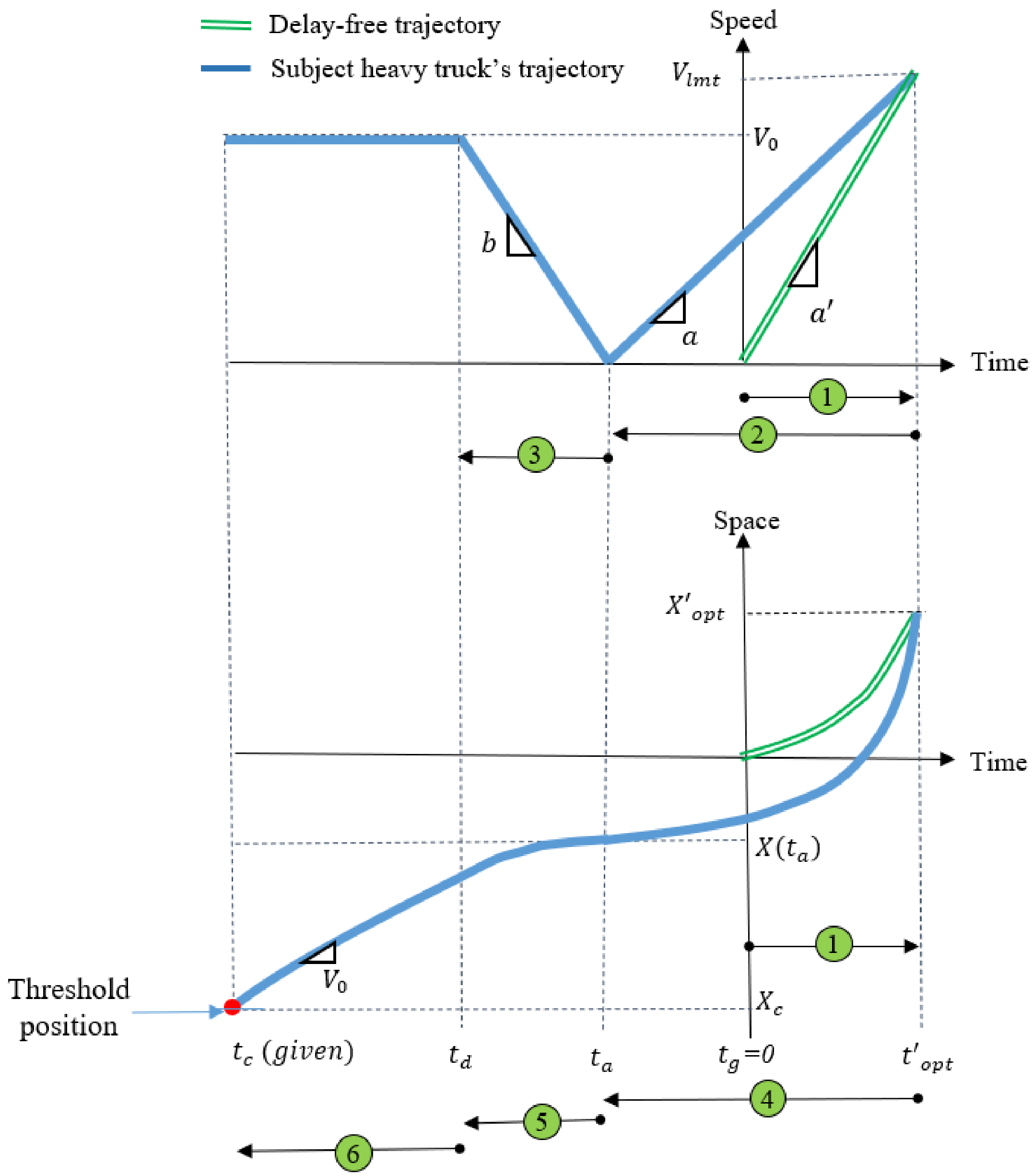


Figure 4-2 Plot of boundary and key variables

Control Type I: A Complete Stop

Figure 4-3 (a) depicts Type I control as speed-time and space-time diagrams. The following steps should be taken to develop the subject heavy truck trajectory.

Step 1 to Step 5: These steps are the same as the first four steps we took to compute t_a and $X(t_a)$ in Eq. (4) and Eq. (8) respectively. Since the start-up point is computed, the next steps imply the equations for the position and the time vehicle should start slowing down at the intersection ($X(t_d)$, and t_d), and the time it should stop at the intersection (t_s).

Step 6: By taking into account the subject control vehicle space-time trajectory between the time interval t_c and t_d, there is a linear relation between t_d and t_c:

$$t_d = \frac{X(t_d) - X_0}{V_0} + t_c \tag{13}$$

Therefore, by inputting $X(t_d)$ from Eq. (10) in Eq. (13), t_d can be re-written:

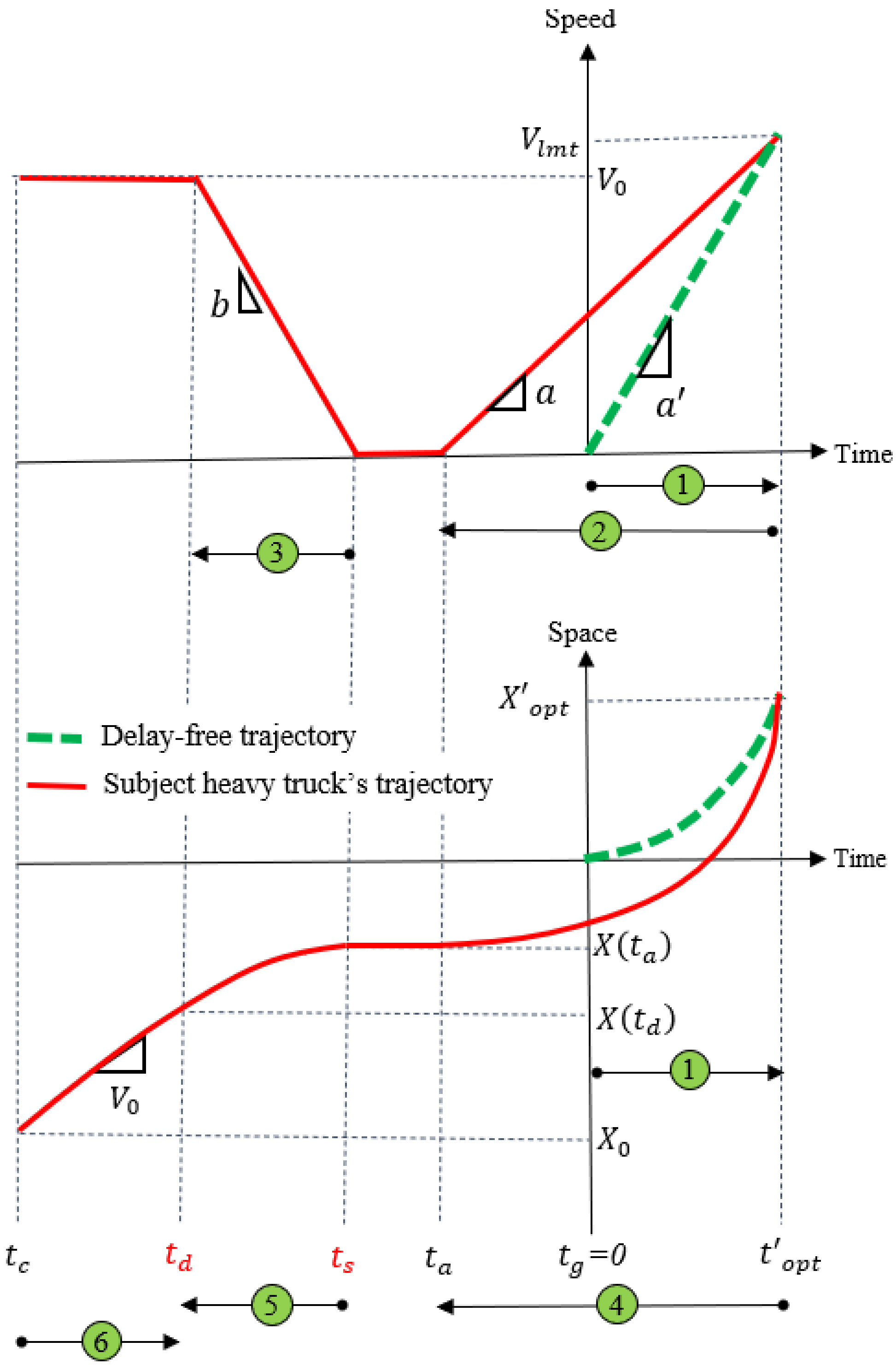
$$t_d = \frac{(V_{lmt})^2}{2V_0}\left(\frac{1}{a'} - \frac{1}{a}\right) - \frac{X_0}{V_0} + \frac{V_0}{2b} + t_c \tag{14}$$

In order to compute t_s, the relation between t_s and t_d is derived from the speed-time plot as:

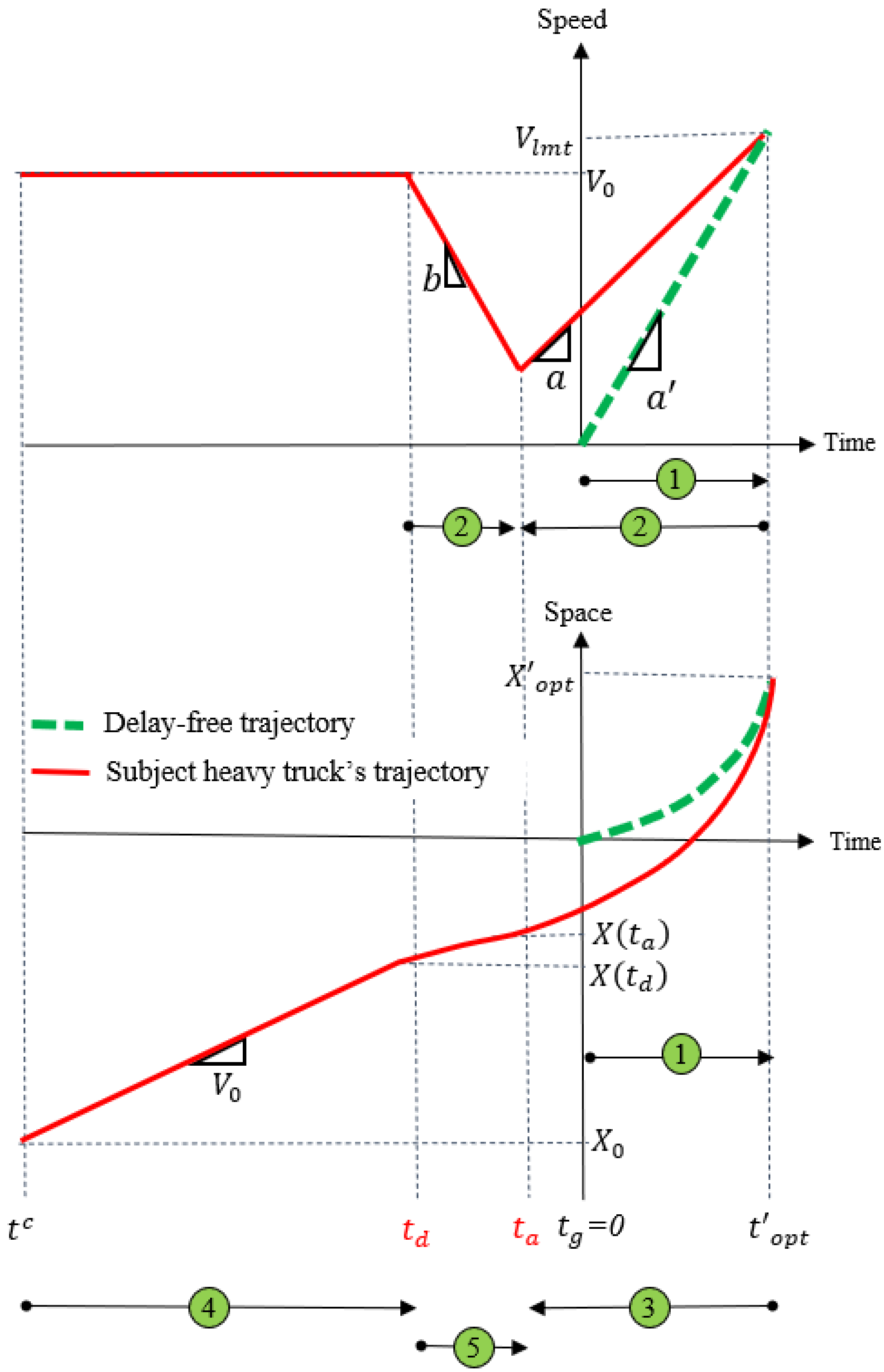
$$t_s = -\frac{V_0}{b} + t_d \tag{15}$$

Finally, by inputting t_d from Eq. (14), t_s is:

$$t_s = \frac{(V_{lmt})^2}{2V_0}\left(\frac{1}{a'} - \frac{1}{a}\right) - \frac{X_0}{V_0} - \frac{V_0}{2b} + t_c \tag{16}$$



(a) Type I control



(b) Type II control

Figure 4-3 Speed-time and space-time graphs for ASP-PST

Control Type II: Slowing Down and Accelerating

This type of vehicle control is depicted in Figure 4-3 (b) as speed-time and space-time plots. The corresponding equations are formulated in the following steps.

Step 1: The first step is the same as before to compute t'_{opt} and X'_{opt} (Eq. (2) and Eq. (3)).

Step 2: By going backward on the speed-time plot from t'_{opt} to t_a, $V(t_a)$ is:

$$V(t_a) = V_{lmt} - a\left(t'_{opt} - t_a\right) \tag{17}$$

By inputting t'_{opt} (Eq. 2), we have:

$$V(t_a) = V_{lmt} - a\left(\frac{V_{lmt}}{a'} - t_a\right) \tag{18}$$

Furthermore, $V(t_a)$ can be obtained by considering t_d to t_a time interval on the speed-time plot:

$$V(t_a) = V_0 + b(t_a - t_d) \tag{19}$$

Setting Eq. (17) and Eq. (18) equal, the relation between t_a and t_d would be:

$$V_{lmt} - a\left(\frac{V_{lmt}}{a'} - t_a\right) = V_0 + b(t_a - t_d) \tag{20}$$

Eq. (20) could be re-written as:

$$t_a = \frac{a'V_{lmt} - a'V_0 + a'bt_d - aV_{lmt}}{a'(b-a)} \tag{21}$$

Step 3: Now to attain the t_a and t_d correlation in space-time plot. In the time interval t_a to t'_{opt}, $X(t_a)$ can be formulated as:

$$X(t_a) = X'_{opt} + \frac{1}{2}a\left(t'_{opt} - t_a\right)^2 - V_{lmt}\left(t'_{opt} - t_a\right) \tag{22}$$

Replacing t'_{opt} and X'_{opt} using Eq. (2) and Eq. (3), Eq. (15) can be re-written as:

$$X(t_a) = \frac{1}{2}a'\left(\frac{V_{lmt}}{a'}\right)^2 + \frac{1}{2}a\left(\frac{V_{lmt}}{a'} - t_a\right)^2 - V_{lmt}\left(\frac{V_{lmt}}{a'} - t_a\right) \tag{23}$$

Step 4: In the space-time plot in the time interval t_c to t_d, $X(t_d)$ can be attained by the following equation:

$$X(t_d) = X_0 + V_0(t_a - t_c) \tag{24}$$

Step 5: In the space-time plot in the time interval t_d to t_a, $X(t_a)$ also can be derived as:

$$X(t_a) = X(t_d) + \frac{1}{2}b(t_a - t_d)^2 \tag{25}$$

By replacing $X(t_d)$ from Eq. (24), we have:

$$X(t_a) = X_0 + V_0(t_a - t_c) + \frac{1}{2}b(t_a - t_d)^2 \qquad (26)$$

Step 6: By equalizing Eq. (23) to Eq. (24), we have the following relation:

$$\frac{1}{2}a'\left(\frac{V_{lmt}}{a'}\right)^2 - V_{lmt}\left(\frac{V_{lmt}}{a'} - t_a\right) + \frac{1}{2}a\left(\frac{V_{lmt}}{a'} - t_a\right)^2 = X_0 + V_0(t_a - t_c) + \frac{1}{2}b(t_a - t_d)^2 \qquad (27)$$

Now, replacing t_a from Eq. (21) in Eq. (27) results in the following quadratic equation:

$$At_d^2 + Bt_d + C = 0 \qquad (28)$$

Where A, B, and C are coefficients of real numbers. By solving Eq. (28), t_d is formulated as follows:

$$t_d = \frac{-B_i \pm \sqrt{B_i^2 - A_iC_i}}{A_i} \qquad (29)$$

$$A = (a - b)(a')^2 ab \qquad (30)$$

$$B = V_{lmt}a'ab(a' + b - a) + (a')^2 b^2 (V_0 - V_{lmt}) - abV_0(a')^2 \qquad (31)$$

$$C = (a - b)(2X_0(a')^2(a - b) + (V_{lmt})^2(a')^2 + (a')^2(V_0)^2 + 2t_cV_0(a')^2(a_i - b_i) + 2a'V_0V_{lmt}(a - a') + ab(V_{lmt})^2 - a'a^2(V_{lmt})^2) \qquad (32)$$

As we assumed the reference point in time is the start time of the green interval ($t_g = 0$) which is zero and all the time points are relative to this reference point, therefore only the negative answer for the t_d is acceptable. Eventually, knowing t_d results in calculating t_a using Eq. (21).

It is noted that all proposed equations are derived assuming the control vehicle is the first vehicle in the queue at the intersection. To generalize equations to work for every control vehicle in the queue, simply $X(t_a)$ should be shifted according to the desired headway and number of the vehicles ahead. For both types of control, the new $X(t_a)$ with n vehicles ahead and desired headway hw_{des}, is:

$$X(t_a)_{new} = dx - n * hw_{des} \qquad (33)$$

The system is designed to follow the mathematical procedure steps precisely to provide control vehicles with designated spots, so they begin the prior start at the intersection to solve the start-up delay problem at intersections. Figure 4-4 depicts ASP-PST procedure briefly as a flowchart.

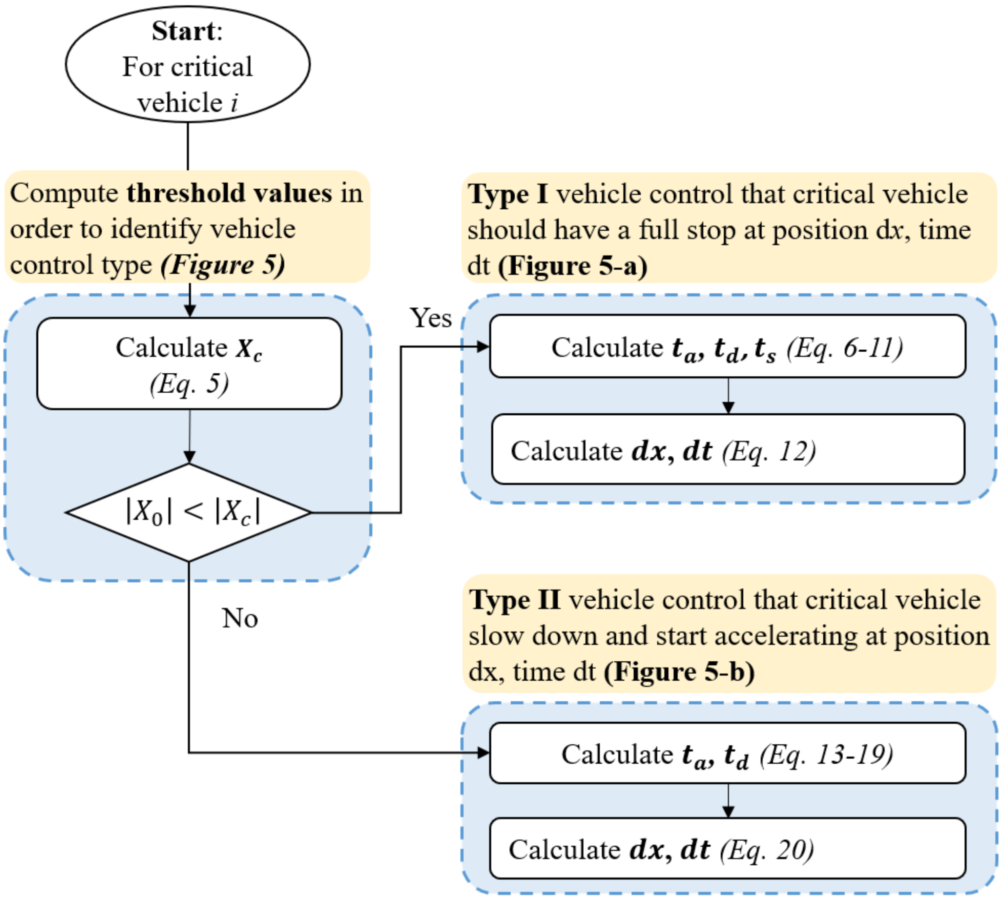


Figure 4-4 ASP-PST traffic control flowchart

Flexibility and Safety

Ensuring the safety and operations of signalized intersections including all system users (e.g., motorists, pedestrians, bicyclists, and transit users) has always been challenging. One question for this system that need to be addressed is the speed of entering vehicles. Planning the vehicle's trajectory can guarantee intersection safety and reduce rear-end collision risks notably.

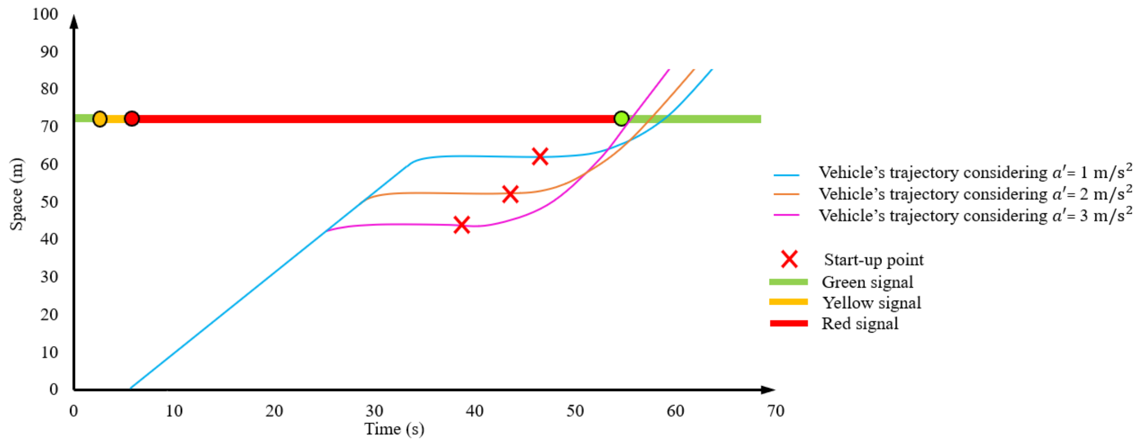


Figure 4-5 Planning trucks trajectories in ASP-PST control system by adjusting ideal acceleration

In Figure 4-5, different trajectories for a heavy truck are demonstrated. By changing the desired acceleration, the start-up point at the intersection will be changed, consequently, vehicles can be controlled to enter the intersection at different times and speeds. Performance-wise vehicles always attempt to enter the intersection at the highest speed possible to minimize the wait. Nevertheless, entering the intersection at high-speed is associated with a risk of collision at the intersection. It is essential to make a trade-off between the performance of the vehicles and safety at the intersection. For instance, when the desired acceleration for the truck sets to 3 ms^{-2} (Pink trajectory), although the truck would enter the intersection with the maximum speed and minimum delay, entering the intersection the moment as the red signal ends, elevate the probability of pedestrian crossing the intersection and as a result increase the accident risk. On the other hand, in the case desired acceleration for the truck sets to 1 ms^{-2} (Blue trajectory), the truck, enters the intersection at a lower speed and more delay. Therefore, upon any collision risk, the truck can be controlled to avoid hazards by modifying the desired acceleration.

CHAPTER 5

EXPERIMENTS AND RESULTS

This section first provides technical/behavior assumptions, then discusses the experiment design.

Assumptions

The control signal collects and processes the dynamic vehicle data from approaching vehicles and recommends a vehicle-specific ASP-PST to the CAVs. The followings are underlying technical/behavior assumptions of this study;

i) All participating trucks are equipped with onboard technology that locates a vehicle, assesses its status, and communicates with a signalized intersection. The CAV messages to signal control contain the latitude and longitude location of the vehicle, speed, heading, and braking rate with a timestamp at 0.1 s intervals. In addition, the system takes into the account weight of the vehicles, and the acceleration rate will be measured accordingly.

ii) The quality of the collected information can vary in terms of latency or unsuccessful vehicle-to-vehicle (V2V) communications. However, we assume that there is no technical issue related to the quality of V2V communications and the accuracy of information.

iii) The drivers or automation will comply with the advisory information. For the simplicity of developing a theoretical framework, a full CAV environment is assumed with full penetration.

Microscopic Traffic Simulation

This study uses a microscopic traffic simulation to evaluate the performance of ASP-PST traffic control, by factoring different vehicle types as well as any number of replications (i.e., different heavy truck percentages) at the intersection network. In this study, we use Gipps' car-following model to generate a detailed longitudinal trajectory of vehicles (*23*). If the approaching vehicle to an intersection is selected as a subject control vehicle, then the ASP-PST control will be applied. It is well-known from the literature that Gipps' model is able to reproduce essential traffic dynamics phenomena. The parameters of Gipps' model in this study are from Gipps. This study uses seven consecutive four-legged intersections. Detailed characteristics of the network are illustrated in Table 5-1.

Table 5-1 Test Network

Number of intersections	7
Distance between intersections	200 m
Number of vehicles	1000
Maximum free-flow speed (V^{lmt})	11 ms^{-1}
Desired acceleration rate (a^{p})	2 ms^{-2}
Intersection width (w)	12 m
Signal cycle	120 s

Numerical Experiments

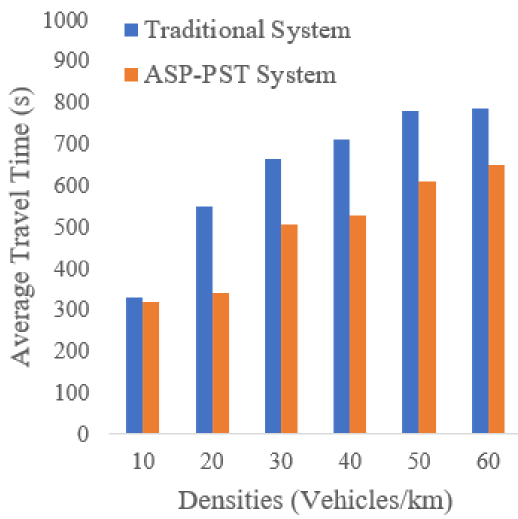
To evaluate the performance of the proposed ASP-PST control system, we carried out a comparison with a traditional signal control. We analyze the feasibility of ASP-PST traffic control in terms of (i) achieving improved mobility, (ii) stability of truck platoons, and (iii) flexibility of the system to guarantee the safety of the intersection via the ASP-PST control model.

Experiment 1: Travel Time

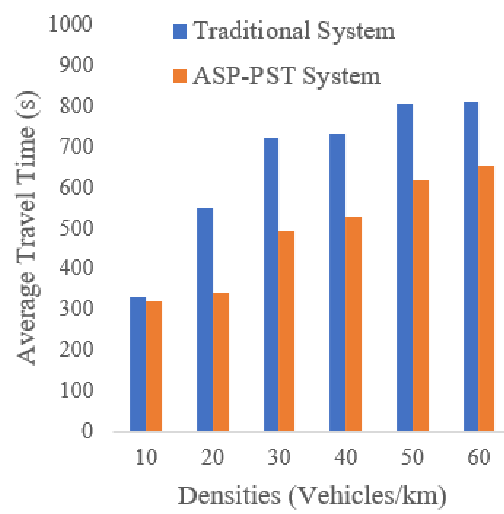
The performance of the two systems can be evaluated based on travel time with different heavy vehicles' proportions on the network. Average vehicles travel time for 5% to 60% proportion of heavy trucks in a network with 1000 vehicles in total, and for different densities (10 vehicles/km, 20 vehicles/km, 30 vehicles/km, 40 vehicles/km, 50 vehicles/km, 60 vehicles/km) is evaluated. The average travel time result is shown in Table 3. In general, the proposed as the density increases the average travel time increase. By comparing the results shown in Table 3, the proposed system could reduce the start-up delay and it is proven in the scenarios mentioned earlier. Vehicles' travel time chosen as the main index to compare the performance of the proposed method with the case without control (Traditional system). To understand the effectiveness of the proposed method, the simulation results conducted by varying the proportion of heavy trucks. It can be seen that with the growth in the percentage of heavy trucks, in most cases the reduction in the travel time is even more highlighted. As the heavy trucks' percentage grows, the ASP-PST method can significantly reduce the travel time by reducing start-up loss. Table 5-2 and Figure 5-1 imply that the ASP-PST method outperformed the case without control in the travel time aspect for almost all densities. The ASP-PST approach has reduced travel time up to 50%.

Table 5-2 Average travel time comparison between traditional system and ASP-PST system

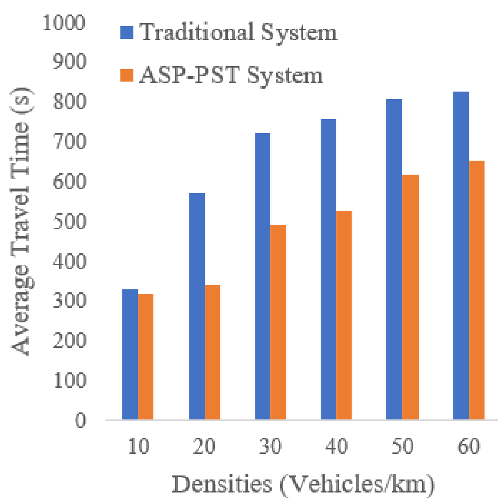
	HV proportion \ Density (veh/km)	**10**	**20**	**30**	**40**	**50**	**60**
Traditional system	**5%**	330	548	665	713	779	788
	10%	332	548	720	733	802	811
	15%	332	570	722	757	807	828
	20%	334	692	795	815	878	887
	30%	339	691	815	831	889	892
	40%	339	686	798	833	884	895
	50%	339	705	804	846	892	902
	60%	348	703	812	852	907	924
ASP-PST system	**5%**	321	340	505	529	611	651
	10%	321	342	491	528	617	654
	15%	320	340	468	527	617	663
	20%	320	339	428	503	628	688
	30%	318	341	447	499	631	691
	40%	321	341	426	518	629	681
	50%	319	335	421	512	630	684
	60%	321	345	446	505	633	672



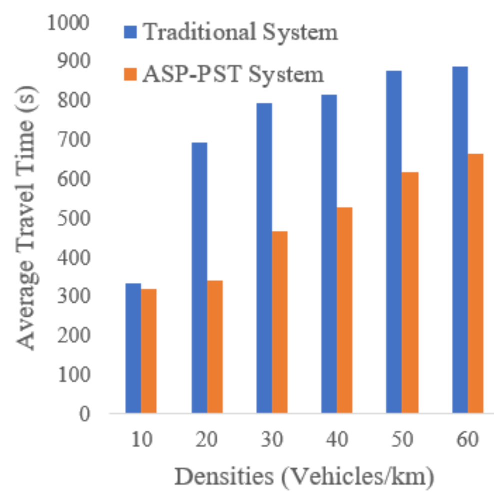
a) 5% truck proportion



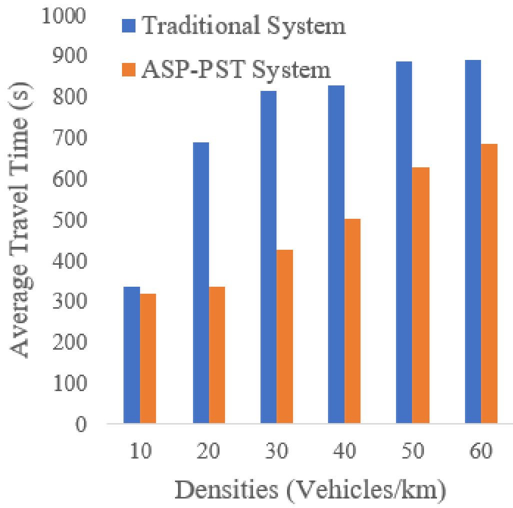
b) 10% truck proportion



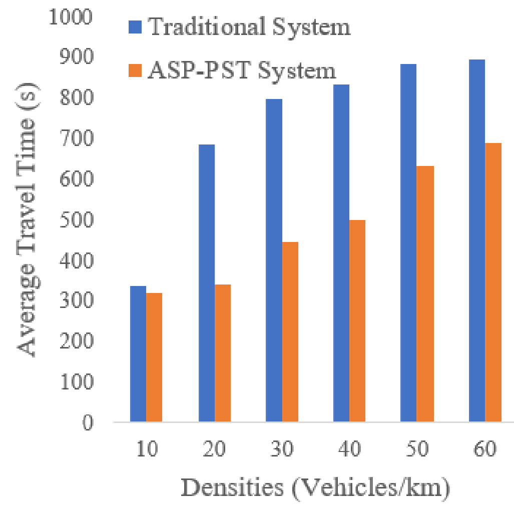
c) 15% truck proportion



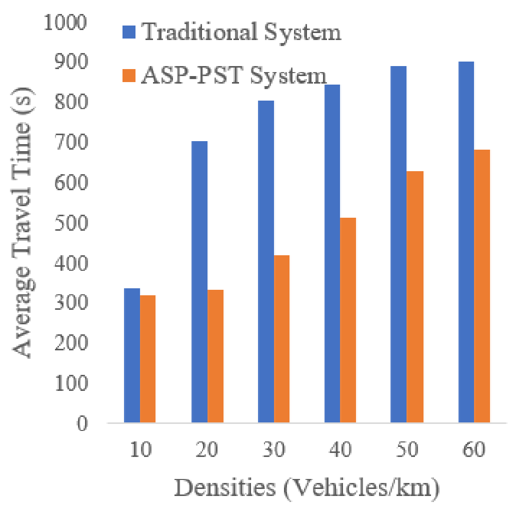
d) 20% truck proportion



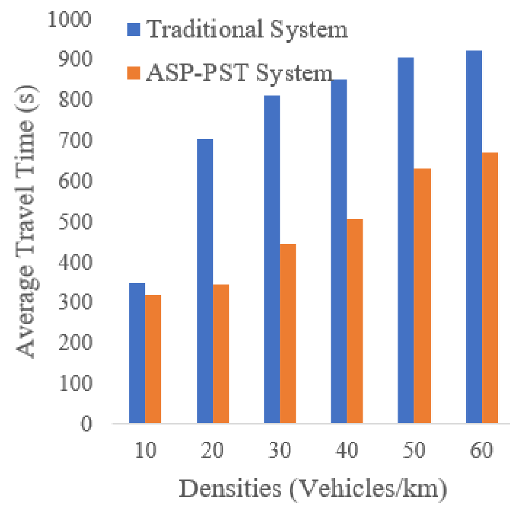
e) 30% truck proportion



f) 40% truck proportion



g) 50% truck proportion



h) 60% truck proportion

Figure 5-1 Average travel time Vs. Density plots for two approaches over different truck proportion

In the case without control the average travel time increases drastically with the increase in the traffic density as more vehicles are affected by the slow start up of the heavy vehicles at the intersections, however in the case of ASP-PST control, the average travel time increase slowly with the increase of the density. Furthermore, the average travel time, regardless of the proportion of heavy vehicles in the traffic network, causes the same pattern through different densities. In the 20~30 vehicles/km densities, it has a noticeable impact on the movements of the following vehicles. In very light traffic (10 vehicles/km), the heavy vehicles start-up delay is not problematic, and there is no bottleneck at the intersections because the gap between vehicles is enough to absorb its impact. In heavy traffic situations, using the ASP-PST method can still be influential, however due to the constraints in the maneuverability of heavy trucks and the saturated gap among the vehicles in the platoon, the travel time difference between two systems has been reduced.

Experiment 2: Gap between Vehicles

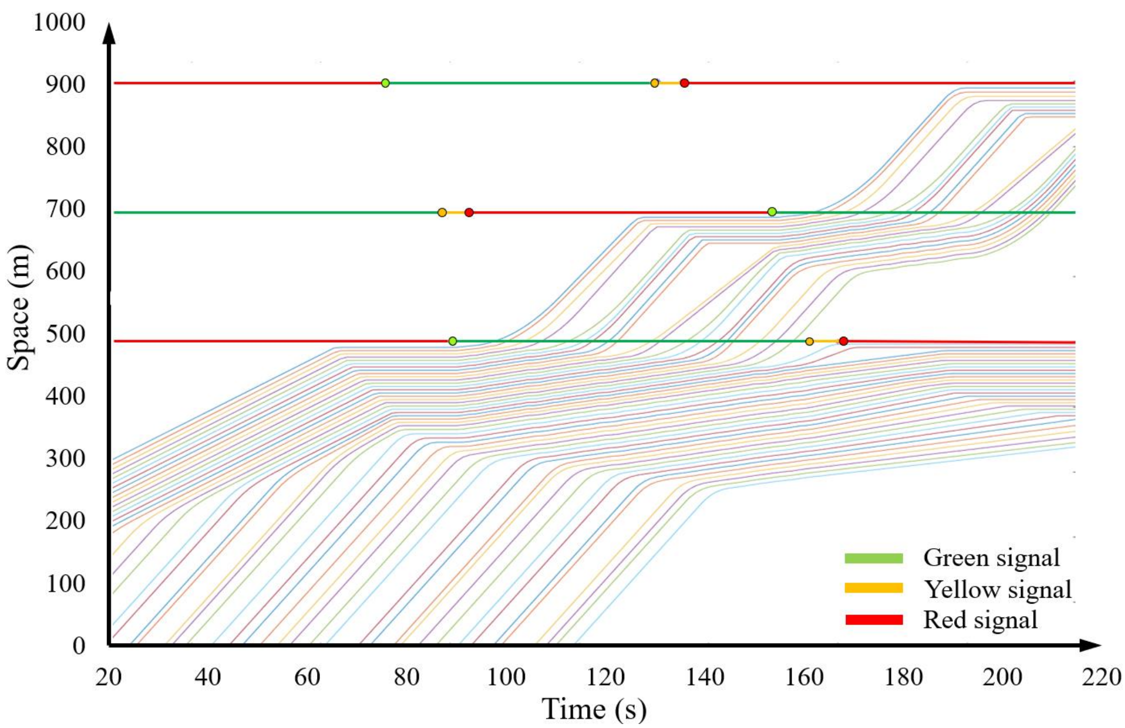
Variance in vehicles' speeds, interfere platooning by creating large gaps between vehicles. Heavy trucks traversing an intersection with undesired lower speed than the road speed limit forms a queue of vehicles behind the truck. This condition gets more severe when the truck percentage is higher. Hanse, by controlling trucks' trajectories as platoon leaders, it is more probable for vehicles to form united platoons. One of the key goals of the proposed system is to harmonize vehicles' gap when their speeds reach the targeted speed (speed limit). According to the fact that in the ASP-PST method, the first vehicle in the queue has the slowest start-up, when this heavy vehicle starts moving, all other vehicles would be able to follow it by keeping desired gap. Consequently, vehicles' trajectories in the traffic network would be smooth and harmonized. Table 5-3 presents the average gap between vehicles and the standard deviation of gaps between vehicles in each platoon 10 seconds after the signal turns green at a few intersections. As shown in Table 4, in the traditional signal control system, gap deviation between vehicles is relatively large. However, in ASP-PST strategy the near-zero standard deviation parameter proves that not only vehicles move smoothly through the intersection, but also chaos in traffic effectively alleviated.

Table 5-3 Average gap comparison between the traditional system and ASP-PST system (The desired gap between vehicles sets to 8 meters)

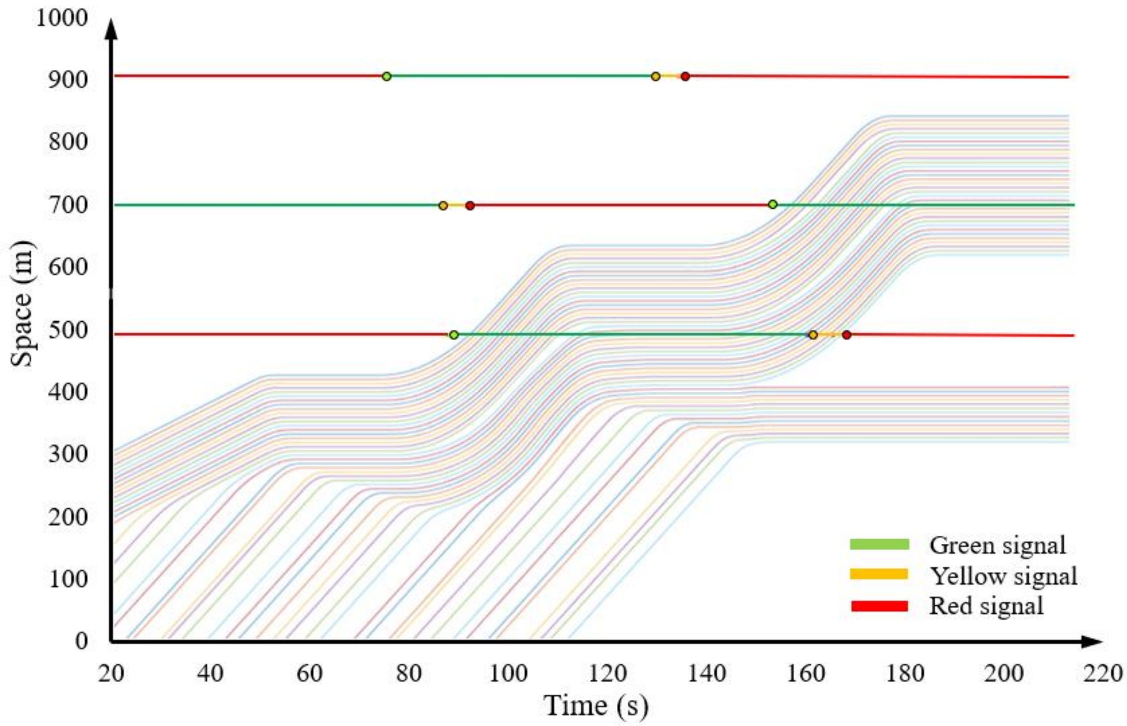
	Traditional System		ASP-PST System	
Time (s)	Ave. Gap (m)	std Gap (m)	Ave. Gap (m)	std Gap (m)
130	9.8	3.5	8.1	0.0

180	7.5	4.3	8.6	2.5
240	11.2	6.5	8.1	0.0
338	21.5	23.6	8.1	0.0
375	13.6	16.3	8.4	1.9

In order to justify the effect of the ASP-PST methodology in platoon formation, Figure 5-2 demonstrates 50 vehicles' trajectories while passing two successive intersections in two different approaches with the 20% proportion of heavy trucks (ASP-PST vs traditional system). In Figure 5-1 (a), due to the slow start-up of heavy trucks in the platoon, their speed is not sufficient to optimize gaps between vehicles. However, in Figure 5-1 (b), it can be observed that all vehicles pile up behind the subject heavy truck to form a coordinated platoon with balanced gaps. Overall, it can be inferred that vehicles in the proposed methodology find more platooning opportunities.



(a) Traditional system

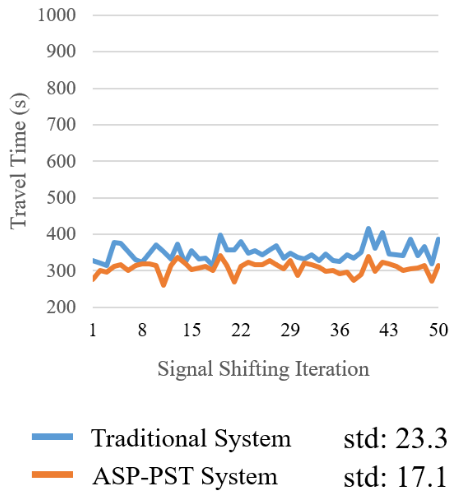


(b) Using ASP-PST traffic control system

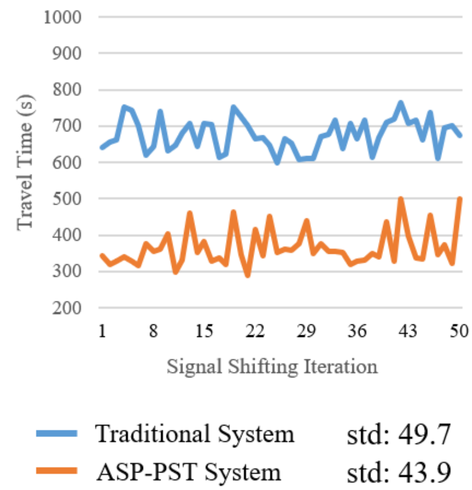
Figure 5-2 Vehicles gap comparison

Experiment 3: Sensitivity of Travel Time to Signal Timing (Travel Time Reliability)

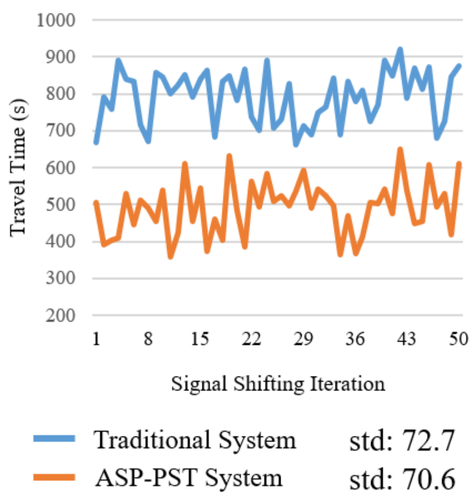
The sensitivity of the average travel time to the signal timing was recorded by modeling 50 different scenarios with changing the start of the signal cycle over different densities with the 20% of heavy trucks proportion. In each iteration, the verge travel time of vehicles that completed their travel by passing the intersections network is captured. Figure 5-3 illustrates the variation in average travel time as a function of the traffic signal beginning point. As shown in Figure 5-3, the change in the signal has the minimum impact on the travel time in the ASP-PST method, while in the traditional method, changing the signal can affect the travel time drastically. The difference between the two systems is more noticeable in higher densities (e.g. 60 vehicles/km). The dependence of travel time on the signal timing presents particular challenges for the traffic control authorities, as it required additional efforts to do any adjustments in the traffic signal.



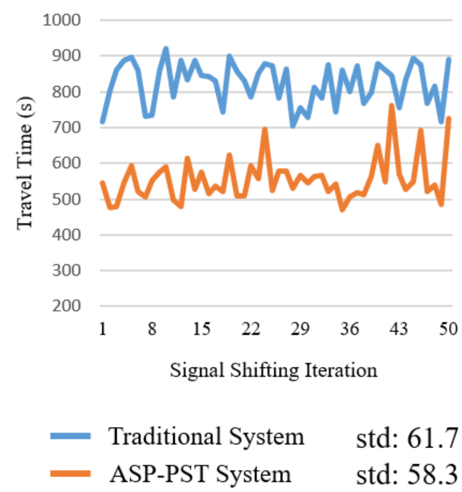
a) Density 10 vehicles/km



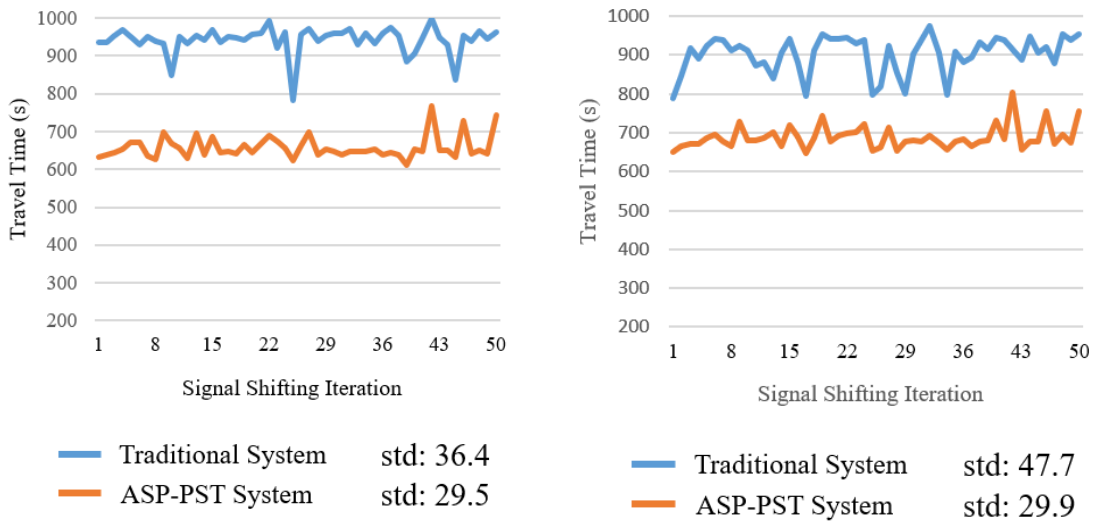
b) Density 20 vehicles/km



c) Density 30 vehicles/km



d) Density 40 vehicles/km



e) Density 50 vehicles/km f) Density 60 vehicles/km

Figure 5-3 The sensitivity of average travel time to the traffic signal cycle starting points over different densities with 20% of heavy trucks

CHAPTER 6
CONCLUSION

Heavy vehicles compared to passenger cars, due to their physical and operational qualities have a greater impact on the surrounding traffic. Heavy trucks at signalized intersections contribute to congestion and bottlenecks because it takes trucks longer than smaller vehicles to get up to the desired speed when the light turns green. This paper proposes a vehicle-specific traffic control that allows heavy vehicles to accelerate in advanced space and time. Therefore, heavy trucks can compensate for the start-up delay. To control the problematic heavy trucks, they are classified into two types, the first type of control will be assigned to those vehicles that are closer to the intersection and they will have a full stop at the intersection. The second type will be applied to the vehicles that are far from the intersection at a certain checking time stamp.

To evaluate the performance of the proposed ASP-PST method, the travel time and the ability to form uniformly spaced platoons have been examined under a mixed traffic environment through a network of seven successive intersections. Compared to traditional signal control, the ASP-PST method attempts to achieve optimum travel time in different proportions of heavy trucks and different traffic densities. The results demonstrate that the proposed solution could improve intersection traffic performance by up to 36% travel time reduction. According to the results, the difference between the ASP-PST method and the traditional system is intensified in mid-range densities (20~30 vehicles/km). This phenomenon is because, in medium traffic, vehicles have a reasonable headway, as a result, any changes in the lead vehicle movement have a noticeable impact on the movements of the following vehicles. Furthermore, giving trucks prior-start time and space would not only optimize vehicles' travel time but also would have a crucial role in increasing the probability of platoon formation across the whole road network. As the key concept behind the ASP-PST is that vehicles would follow the slowest vehicle at the intersection, and they would be controlled in a way to keep the desired headway with the lead vehicle. Moreover, the proposed system is less dependent on the signal timing compared to the traditional system which can be beneficial for the traffic control authorities in the urban areas.

While this method has a promising result, it must sacrifice upstream space to alleviate the delay in heavy vehicles. The green signal of each heavy truck is automatically controlled to have enough acceleration time and space to pass through the intersection, just as on the freeway on-ramp acceleration lane. Therefore, doing a sensitivity analysis can help to understand whether using the proposed method is worthwhile considering the space compromise. It should be noted that the results are achieved based on a test environment with a series of independent intersections; however, this study can further be extended to develop the proposed idea to alleviate start-up delays in cooperative traffic signals.

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VITA AUCTORIS

NAME:	Saeideh Esmaeili
PLACE OF BIRTH:	Isfahan, Iran
YEAR OF BIRTH:	1993
EDUCATION:	Eftekhar High School, Isfahan, Iran, 2011
	Shahid Beheshti University, B.Sc., Tehran, Iran, 2015
	University of Windsor, M.Sc., Windsor, ON, 2022